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Technical Report

Funding was provided by the Woods Hole Branch
of the U.S. Geological Survey.

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Technical Report

Prepared for the U.S. Department of the Interior, U.S. Geological Survey, Woods Hole, Massachusetts under joint agreement with Woods Hole Oceanographic Institution.

Approved for Distribution:

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ABSTRACT:

The Massachusetts Bays Program made bottom pressure and water velocity observations in Massachusetts and Cape Cod Bays during 1990 and 1991. In the Bays, the sea surface elevation appeared to rise and fall in phase with equal amplitudes at each diurnal or semidiurnal tidal frequency. There is some amplification in Boston and Provincetown harbors. The semidiurnal tides (particularly the M2 constituent) dominate. Massachusetts and Cape Cod Bays are part of the Gulf of Maine/Bay of Fundy system which is resonant near the semidiurnal tidal frequency. This resonance amplifies the importance of the semidiurnal tides so that diurnal and higher harmonic tides become negligible. The sea level tides force currents which move with the same frequencies, but whose amplitudes are affected by the bathymetry. The strongest currents exist in the channel between Race Point and Stellwagen Bank where tidal currents exceed 1 knot. Analysis of current records for their tidal signal is complicated by internal tides which contaminate the records. These internal waves at tidal frequency exist on the stratification in the water column, and disappear during winter well-mixed times. At other times they must be considered as a significant source of energy for mixing and resuspension of sediments.

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1. INTRODUCTION:

1.1 The Massachusetts Bays Program

The Massachusetts Bays Program, administered through the Massachusetts Coastal Zone Management Office and the U.S. Geological Survey, Woods Hole Branch, is designed to (1) increase our knowledge and understanding of the Boston Harbor, Massachusetts Bay, and Cape Cod Bay system, (2) inform the public and facilitate communication about the problems and issues facing Massachusetts Bay, and (3) evaluate and improve management strategies for this system. The long-term objective of the program is to provide a comprehensive evaluation of the sources and effects of contaminants in the Massachusetts and Cape Cod Bays and to produce an area-wide management plan for water quality protection and enhancement.

The physical oceanography component of this program was designed to provide the first bay-wide description of the circulation and mixing processes on a seasonal basis. The field work was undertaken by scientists from the Woods Hole Oceanographic Institution, the University of Massachusetts at Boston, the University of New Hampshire, and the U.S. Geological Survey at Woods Hole. Because horizontal and vertical transport is important to biological, chemical, and geological processes in Massachusetts and Cape Cod Bays, this physical oceanographic study has broad applications and will improve our ability to manage and monitor the water and sediment quality of the Bays.

The observation program, conducted between April 1990 and June 1991, consisted of moored observations to study the current flow patterns and water property variations, hydrographic surveys to document the changes in water properties, high resolution spatial surveys of velocity and water properties to provide information on the spatial variability of the flow, drifter deployments to measure the water parcel trajectories, and acquisition of satellite images to provide a bay-wide picture of the surface temperature and it spatial variability. The moored time-series component consisted of current meter, bottom pressure, temperature and conductivity observations at critical locations shown in Figure 1. Currents were measured with Vector Measuring Current Meters (VMCM) (Weller and Davis, 1980) at 4 meters depth directly below the surface buoys, Vector Averaging Current Meters (VACMs) (McCullough, 1975) in the deeper waters, and an Acoustic Doppler Current Profiler (ADCP) (Pettigrew and Irish, 1985) in Stellwagen Basin. Sea level was measured with bottom pressure instruments across the mouth of Massachusetts Bay and a National Ocean Survey tide gauge in Boston Harbor.

Tides play a minor role in the long-term horizontal transport of material in Massachusetts and Cape Cod Bays since they are periodic and move material back and forth. There is no net transport associated with tides, except as non-linear tidal rectification. However, tidal oscillations contain the largest energy in the sea surface elevation and currents, and so play a major role in determining bottom drag, vertical mixing, etc. which has an important impact on the dispersal of material. This report concentrates on the analysis of these observations for their tidal content. For a more general report on the Massachusetts Bays physical oceanographic program and results, see Geyer et al., (1992).

1.2 Tides of the Gulf of Maine and Massachusetts Bay

The tides in Massachusetts Bay are forced by the tides in the Gulf of Maine which are in turn driven by the tides of the North Atlantic. The tides in the North Atlantic are the ocean's response to the gravitational attraction of the sun and the moon. These tides have wavelengths of order 9,000 km and periods of about once-a-day (diurnal) and twice a day

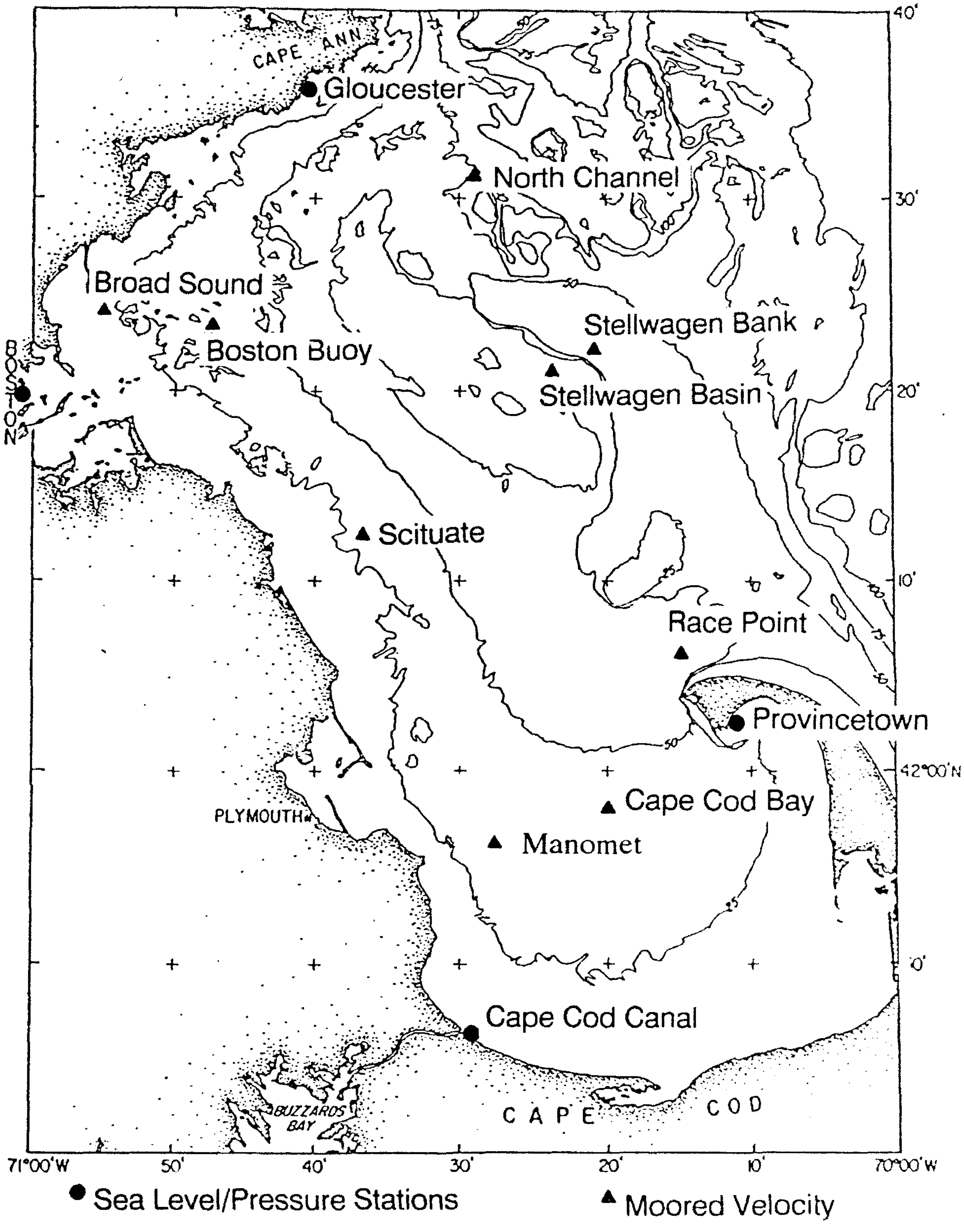


Figure 1. Locations of the bottom pressure, surface elevation, and moored current observations made during the Massachusetts Bays Program field effort.

(semidiurnal). Since the wavelength is much greater than the water depth (4 to 6 km), the waves behave as shallow water waves whose velocity is controlled by the water's depth. The free wave response in the North Atlantic basin appears as an edge wave rotating counterclockwise around an amphidromic point (a point of no elevation change) in the center of the North Atlantic. This is illustrated in cotidal charts of the North Atlantic for the main diurnal and semidiurnal tidal frequencies (Figure 2). Along the east coast of the United States, the tide appears as a wave propagating down the coast, passing the mouth of the Gulf of Maine. This sea surface elevation change over Browns and Georges Bank excites the tides in the Gulf of Maine and Bay of Fundy system.

The Gulf of Maine system is in near resonance at about the semidiurnal frequency (Garrett, 1972 & 1974), which causes a larger than normal tidal range, especially in the Bay of Fundy. The analysis of bottom pressure records in the Gulf of Maine by the response method gives the response function of the Gulf of Maine to the tidal potential (the gravitational attraction of the sun and moon). (Note that this is different from the actual forcing which is a function of the response of the North Atlantic to the gravitational forcing). The response function of the Gulf of Maine to gravitational potential determined from a 400 day bottom pressure record from Jordan Basin in the Gulf of Maine (Irish, 1990), shows a peak in the amplitude response about the N2 tidal frequency (1.895673 cpd), just below the principal lunar tidal frequency (M2 at 1.932274 cycles per day). The response function gives the relative importance of each tidal line relative to the gravitational forcing. The N2 and M2 are amplified about 2.3 and 2.1 (relative to an equilibrium tide). The principal solar tide (S2 at 2.0 cycles per day) at a higher frequency, farther above the resonance frequency than the M2, is only amplified by a factor of 1.0. The resonance amplifies the importance of the semidiurnal tides over the diurnal tides in the Gulf of Maine, and amplifies the importance of the monthly modulation (interaction of the M2 and N2 frequencies) over fortnightly modulation (the interaction of the M2 and S2 frequencies). This is clearly seen in the bottom pressure record from Stellwagen Bank (Figure 3). The monthly modulation in amplitude due to the beating of the N2 and M2 frequencies dominates over the fortnightly modulation due to the beating of the M2 and S2 frequencies. This is the reverse of what is seen in much of the world's oceans.

The response function over the diurnal band is nearly flat (as compared with the peak observed in the semidiurnal band) and has an amplitude response of about 0.37. This increased amplitude at the semidiurnal frequency not only occurs in the Bay of Fundy, but throughout the Gulf of Maine and Massachusetts Bay. The effects of this resonance and tidal dissipation in the Gulf of Maine also extend back out into the North Atlantic, and locally distort the tidal wave traveling down the coast, causing a phase lag in the region of the mouth of the Gulf of Maine. (Note how the co-phase lines in Figure 2 show a lag in the region just outside the Gulf for the M2 (top), but not the O1 (bottom).)

The Massachusetts and Cape Cod Bays system is part of the Gulf of Maine, although somewhat separated from it by Stellwagen Bank. The tides in the Gulf of Maine drive the tides in Massachusetts and Cape Cod Bays. The resonance of the Gulf of Maine system simplifies the tidal analysis as discussed below. During the Massachusetts Bays field program, the tidal elevation was measured by several bottom pressure instruments as well as coastal sea level at sites shown in Figure 1. The bottom pressure (Figure 3) and current records (Figure 4) taken on Stellwagen Bank were chosen as representative records of the tide forcing (elevation and flow) of Massachusetts Bays and used for more detailed analyses. Figure 5 shows power density spectra for the pressure (sea level) and currents at this station. The semidiurnal tidal peaks dominate the variance of both sea level and current velocity.

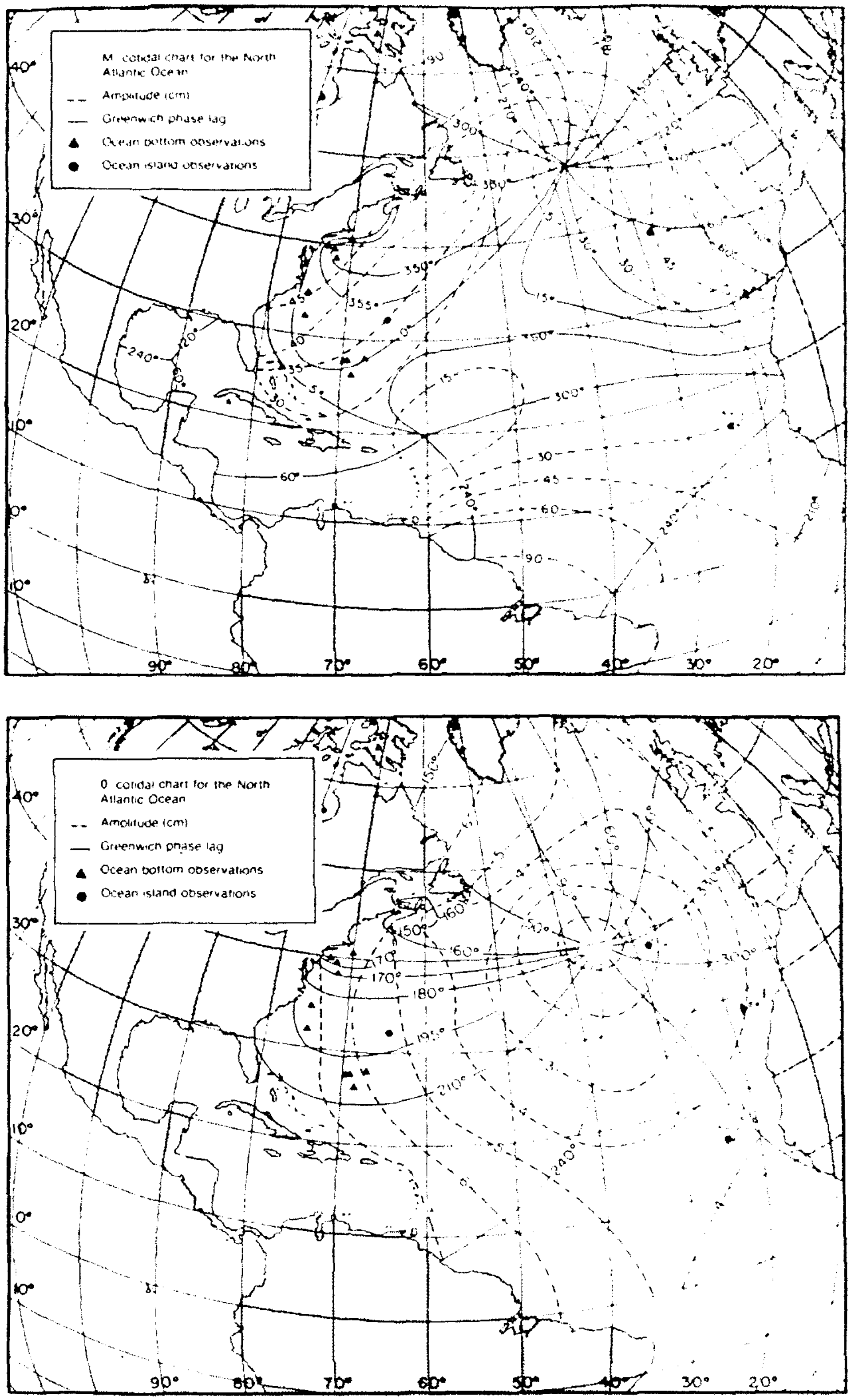


Figure 2. Cotidal charts of the North Atlantic for the principal diurnal and semidiurnal tidal lines. The lines of equal amplitude (co-range lines) are shown as dashed lines, and the lines of equal phase (co-phase lines) are shown as solid lines. (From Brown and Moody, 1987)

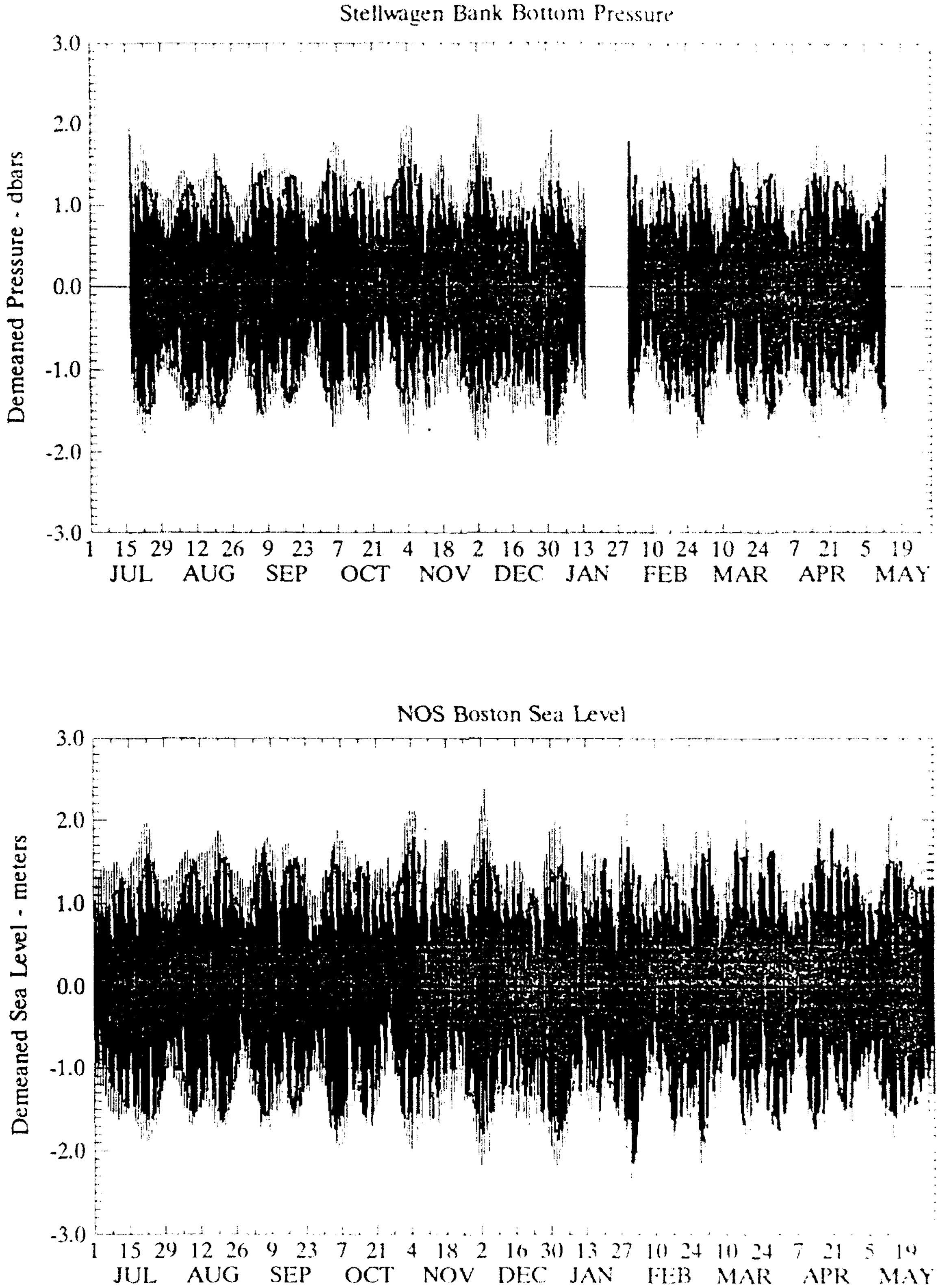


Figure 3. The Stellwagen Bank bottom pressure record from 29 meters depth (top) and NOS Boston Harbor sea level record (bottom) show the dominant M2 tide with daily inequality in the amplitude as well as the monthly and fortnightly modulation.

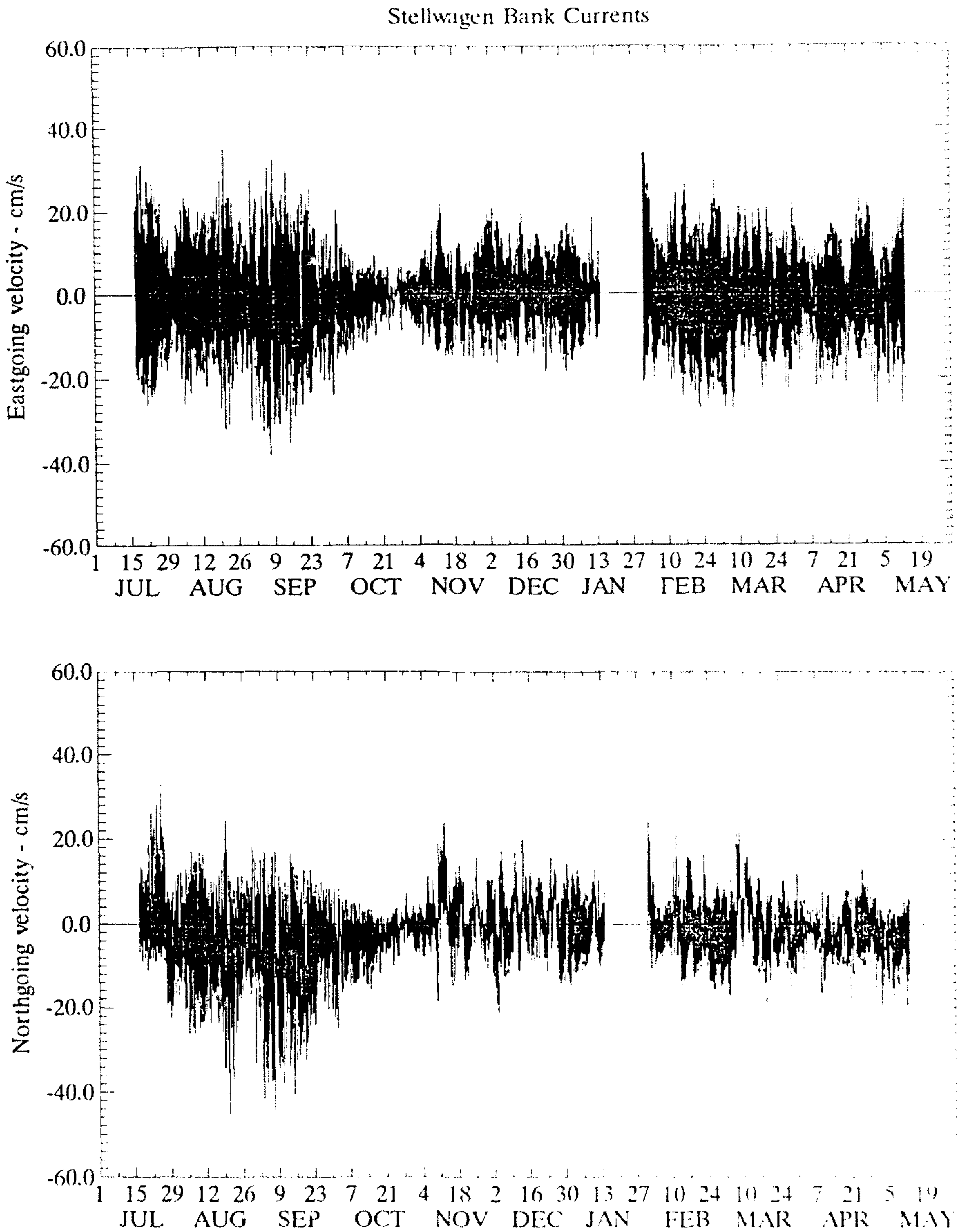
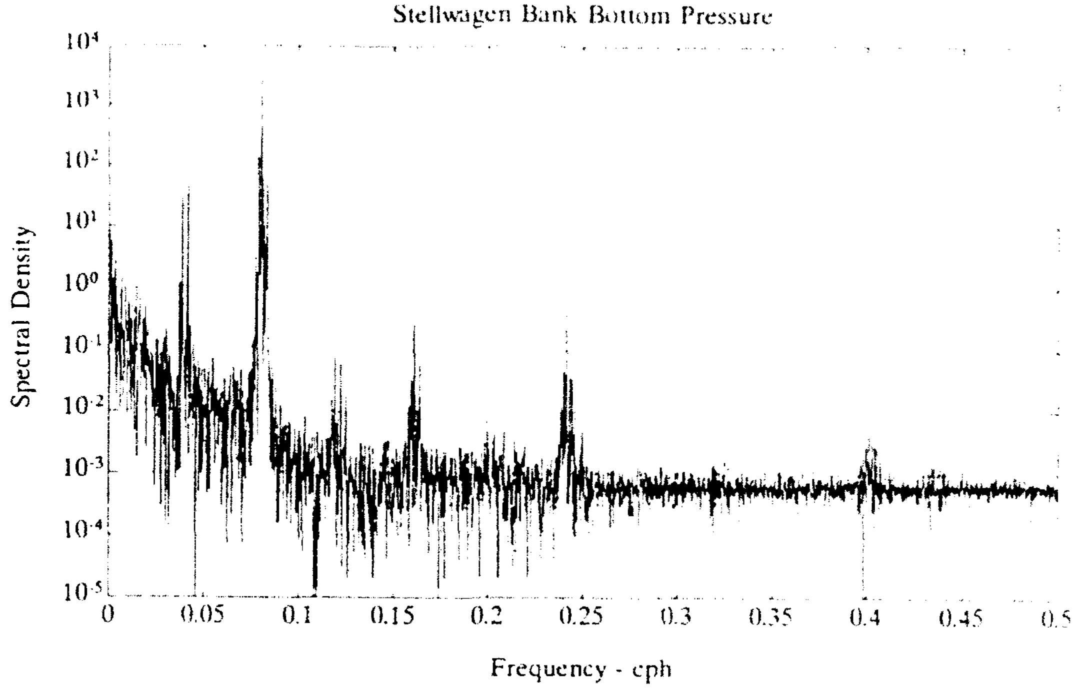


Figure 4. The Stellwagen Bank bottom current records at 27 meters depth, 2 meters above the bottom, again show the dominant semidiurnal tide with seasonal variations due to internal tidal effects.



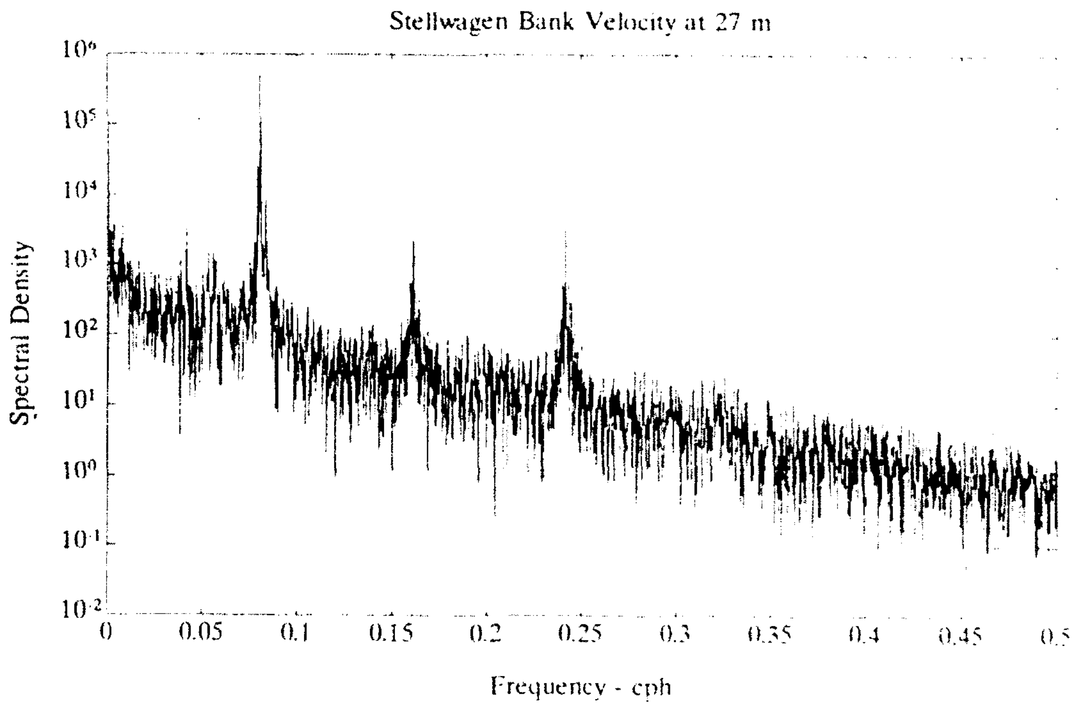


Figure 5. Stellwagen Bank spectra of bottom pressure (from time series in Figure 3 shown at top) and velocity (from time series in Figure 4 shown at bottom). The semidiurnal tides (0.08 cph) are the dominant energy in both plots, with the diurnal (0.04 cph), quarter-diurnal (0.16 cph) and sixth-diurnal (0.24 cph) tidal bands having energy above background sea level fluctuations. In the pressure spectrum, the third-diurnal (0.12 cph) is seen and in the current spectrum the inertial frequency (0.056 cph) barely rises above background, and the diurnal signal is only as strong as the quarter-, and sixth-diurnal tides.

1.3 Tidal Analysis Techniques

There are three tidal analysis techniques which were used to analyze the Massachusetts Bays records. (1) The classic method of harmonic analysis was devised by Lord Kelvin in 1867, expanded by the work of Sir George Darwin, A. Doodson and others and adopted by the U.S. Coast and Geodetic Survey (Schureman, 1940). Dennis and Long (1971) produced a computer program using this method which has been further revised to the program used here (Irish and Brown, 1986). (2) The response method was devised by Munk and Cartwright (1966) to separate the astronomical gravitational forcing function from the ocean's response. Its methodology allows other inputs such as radiational tides (wind-induced sea level changes) and runoff to be formally analyzed. (3) The least squares method implemented by Foreman (1977) is based on the methods suggested by Godin (1972), and has the advantage of handling records with data gaps. The U.S. Geological Survey at Woods Hole version of this program was used for the analyses here. Each method has advantages and all were used on the pressure and current records from Stellwagen Bank for a detailed comparison and evaluation.

2. TIDES - SURFACE ELEVATION:

2.1 Stellwagen Bank Pressure

The Stellwagen Bank bottom pressure record was selected because it was not in a bay or harbor, such as Boston sea level recorder or the Gloucester and Provincetown Coast Guard pressure records, so might better represent the force driving the tides in the Massachusetts Bay and Cape Cod Bay system. Table 1 shows the comparison of the results from the three methods for the ten largest amplitude diurnal, semidiurnal and higher harmonic frequencies. The pressures have been divided by the average sea water density and gravitational acceleration to convert them to an equivalent sea water elevation in cm. No correction for atmospheric pressures were made. The factor used is 99.55 cm/dbar (taking an averaged density of 1025 kg per cubic meter and a gravitational acceleration of 9.80 meters per second squared), so the amplitudes are tabulated in cm elevation. The phase is reported relative to the passage of the sun or moon over the Greenwich meridian and called the Greenwich epoch. The amplitudes and phases are reported at the usual harmonic tidal constituent frequencies. This allows a prediction of the tides to be made for any future or past time.

The results from the different techniques are in good agreement except at the S2 frequency. The response analysis method is quite difference here since it also considered a "radiational" component at the S2 frequency. The radiational tide is a signal at the S2 semidiurnal frequency because it is caused by radiation effects of the sun, such as a sea breeze which is caused by differential heating of the sun over land. The response method selects an amplitude and phase for the gravitational component (listed before the parentheses) which was the fit selected by the program in order to produce a smooth admittance to the gravitational forcing (see Zetler and Munk, 1975). The response analysis uses the summed tidal energy of all constituents in the semidiurnal band and only allows the admittance to change at a user-selected rate (see Cartwright et al., 1969). Therefore, the analysis selects the amount of S2 which is consistent with a smooth admittance of all constituents in the band, and then selects an amount of radiational tide to add to the gravitational tide to best fit the observed S2 tide. This radiational component is listed in parentheses after the gravitational component in the response column of Table 1, and is nearly out of phase with the gravitational component. Neither of the other two analysis techniques separate out a radiational component. In the analysis of tides in coastal regimes, such as the CODE experiment (The CODE Group, 1983) on the northern California shelf,

TABLE 1 - Stellwagen Bank Bottom Pressure Tidal Analysis Comparison for the three tidal analysis methods.

Tide Line Darwin Symbol Freq. (cpd)	Harmonic H(cm) G(degrees)	Response H(cm) G(degrees)	Least Squares H(cm) G(degrees)
Q1 0.893244	2.10 359.8	2.07 171.2	2.0 164.0
O1 0.929536	10.82 186.7	10.71 185.3	10.9 186.0
P1 0.997262	4.57 175.2	4.62 203.3	4.2 201.7
K1 1.002738	13.80 203.5	13.73 204.0	13.5 204.4
N2 1.895982	27.15 72.5	26.80 77.0	28.0 74.1
M2 1.932274	122.75 108.3	122.70 108.2	122.8 108.4
S2 2.000000	18.94 141.9	30.50(8.90) 145.6(335.2)	18.9 142.3
K2 2.000000	5.15 144.7	6.40 148.9	5.2 142.0
M4 3.864547	1.26 341.0	- -	1.3 343.4
M6 5.864547	1.07 287.3	- -	1.2 283.1

Note: (1) decibars were converted to cm by multiplying by 99.55
(2) the semidiurnal radiational tide from the response analysis is listed in parentheses and is added to the gravitational tide to get the observed tide.

the radiational component has proven to be considerable, and often confuses conventional tidal analysis in these regions. It is not clear what is the best interpretation to put on this result, but it should serve as an indicator that these effects need more attention.

The admittance function from the response analysis (Table 2), relative to the gravitational tidal potential is plotted in Figure 6. The response function can only be estimated at the tidal frequencies where we know the forcing function. These discrete points are connected with a solid line in the diurnal and semidiurnal bands. Outside of these bands we have no information on the ocean's response function. The diurnal admittance is relatively flat with modest phase shift. The semidiurnal frequency amplitude gain changes by a factor of 3 with large accompanying phase shift. If the diurnal response of 0.4 is typical of a non-resonant response, and the M2 response of 2 is due to the resonance, then a gain of 5 is estimated, in agreement with that estimated by Garrett (1972). Again this emphasizes the semidiurnal resonance which helps makes the M2 the largest signal present.

It is also obvious from Figure 5 and Table 1 that most of the energy in the pressure (sea level) fluctuations on Stellwagen Bank is in the principal lunar constituent, M2. An analysis of the variance in the record (out to the Nyquist frequency of 0.5 cph) shows that the total variance (energy) in the diurnal tidal band is only 2.0% of the total record variance. However, the tidal analysis by the harmonic method predicts 99.6% of the energy in diurnal band. The prediction is good, but the diurnal tides are small compared with the semidiurnal tides, as was seen in the spectrum in Figure 5. After a full tidal analysis, the residual variance, which contains the low-frequency weather-induced background sea level fluctuations, accounts for only 2.0% of the total observed energy, i.e. the tides are 98% of the total energy. This is illustrated in a bar graph in Figure 7.

The energy in the semidiurnal tidal band on Stellwagen Bank accounts for 95.3% of the total observed variance in pressure record (the sea level). Again, the harmonic analysis predicts 99.6% of the energy in the semidiurnal tidal band. The principal lunar constituent, M2, represents 96.3% of the variance in the semidiurnal band, or 92.1% of the total record variance. Therefore, because of the response of North Atlantic and the resonance of the Gulf of Maine system, the semidiurnal tides are amplified and dominate. The M2 is amplified more than the S2 which enables one to represent the surface elevation as a single sine wave with the amplitude and phase of the M2 constituent and to explain more than 92% of the observed pressure (sea level) energy. This is shown in Figure 7.

Using Defant's (1961) characterization of tidal type, the ratio of diurnal (K1 + O1) to semidiurnal (M2 + S2) amplitudes is 0.17 which is less than 0.25, so the tides are classified as semidiurnal. Using this criterion along the northern east coast of the United States, the tides are classified as semidiurnal or mixed with the ratio varying from 0.17 to 0.28 depending on the location. Again this says that diurnal tides are less important relative to the semidiurnal and can probably be ignored to the first order in Massachusetts Bay.

2.2 Compound Tides on Stellwagen Bank

Figure 5 also shows that there are significant higher harmonics of the tides present. These higher harmonics (third-diurnal, quarter-diurnal, and sixth-diurnal frequencies) are called overtides (analogous to overtones) or compound tides and are an interesting study in themselves. Figure 8 shows the spectra in Figure 5 expanded to resolve the normal and higher harmonic bands and the principal tidal lines are identified by their Darwin symbol. Although energy at the higher harmonic frequencies is present in the gravitational driving force, it is not nearly so large as seen in coastal regions. Compound tides are most often associated with non-linear interactions of the principal tidal lines which are attributed to

TABLE 2 - Stellwagen Bank Bottom Pressure Response Analysis

Reference is Tidal Potential G_2^1, G_2^2, R_2^2 (Cartwright et al., 1969)

***** DIURNAL TIDES *****

FREQUENCY	ADMITTANCE		TIDAL LINES				RESULTING	
	OBS LEADS REF BY PHASE		MOST SIGNIF		MOST CENTRAL		CONSTITUENTS	
CPD	AMP	PHASE		CPD		CPD	H	G
0.892935	0.004256	8.817	Q1	0.893244	Q1	0.893244		
0.929536	0.004145	-5.234	O1	0.929536	O1	0.929536	10.71	185.3
0.966137	0.004016	-16.746	M1	0.966446	M1	0.966446		
1.002738	0.003742	-24.015	K1	1.002738	K1	1.002738	13.73	204.0
1.039339	0.003250	-25.500	J1	1.039030	J1	1.039030		
0.893244	0.004255	8.695	O1	0.929536	Q1	0.893244	2.07	171.2
0.997262	0.003796	-23.250	K1	1.002738	P1	0.997262	4.62	203.3

***** SEMIDIURNAL TIDES *****

FREQUENCY	ADMITTANCE		TIDAL LINES				RESULTING	
	OBS LEADS REF BY PHASE		MOST SIGNIF		MOST CENTRAL		CONSTITUENTS	
CPD	AMP	PHASE		CPD		CPD	H	G
1.859071	0.030598	-42.526	MU2	1.864547	2N2	1.859690		
1.895672	0.022328	-75.087	N2	1.895982	N2	1.895982		
1.932274	0.019538	-108.232	M2	1.932274	M2	1.932274	122.70	108.2
1.968875	0.016177	-130.759	L2	1.968565	L2	1.968565		
2.005476	0.007769	-149.227	S2	2.000000	K2	2.005476	6.40	148.9
1.895982	0.022287	-75.392	M2	1.932274	N2	1.895982	26.80	77.0
2.000000	0.009394	-145.848	S2	2.000000	S2	2.000000	30.50	145.6

***** RADIATIONAL TIDES *****

FREQUENCY	ADMITTANCE		TIDAL LINES				RESULTING	
	OBS LEADS REF BY PHASE		MOST SIGNIF		MOST CENTRAL		CONSTITUENTS	
CPD	AMP	PHASE		CPD		CPD	H	G
2.000000	0.160137	24.903	S2	2.000000	S2	2.000000	8.90	335.2

RECORDED VARIANCE = 0.825100E+00 (in dbars)
PREDICTED VARIANCE = 0.810263E+00 = 98.2% of recorded variance
RESIDUAL VARIANCE = 0.148365E-01 = 1.8% of recorded variance

Note: The analysis used 3 lags of -48, 0 and 48 hours.

Note: In the diurnal band, the first five frequencies are at cycle per month intervals centered on the M1 frequency. The next two frequencies are centered on the Q1 and P1 lines. For the semidiurnal band, the first five lines are at cycle per month intervals centered on the M2 frequency. The next two lines are at the N2 and S2 frequency. The radiational tide is only reported at the S2 frequency.

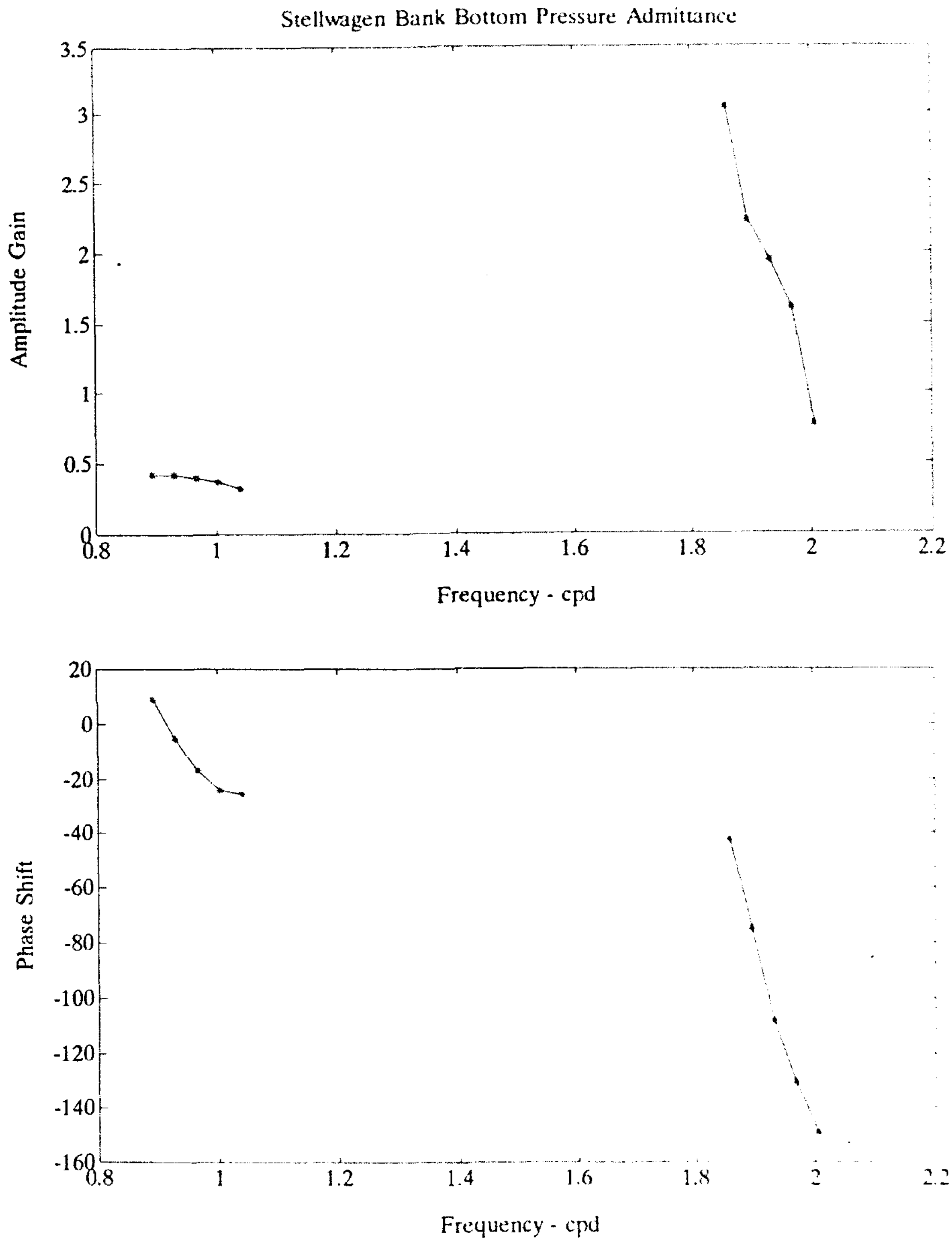
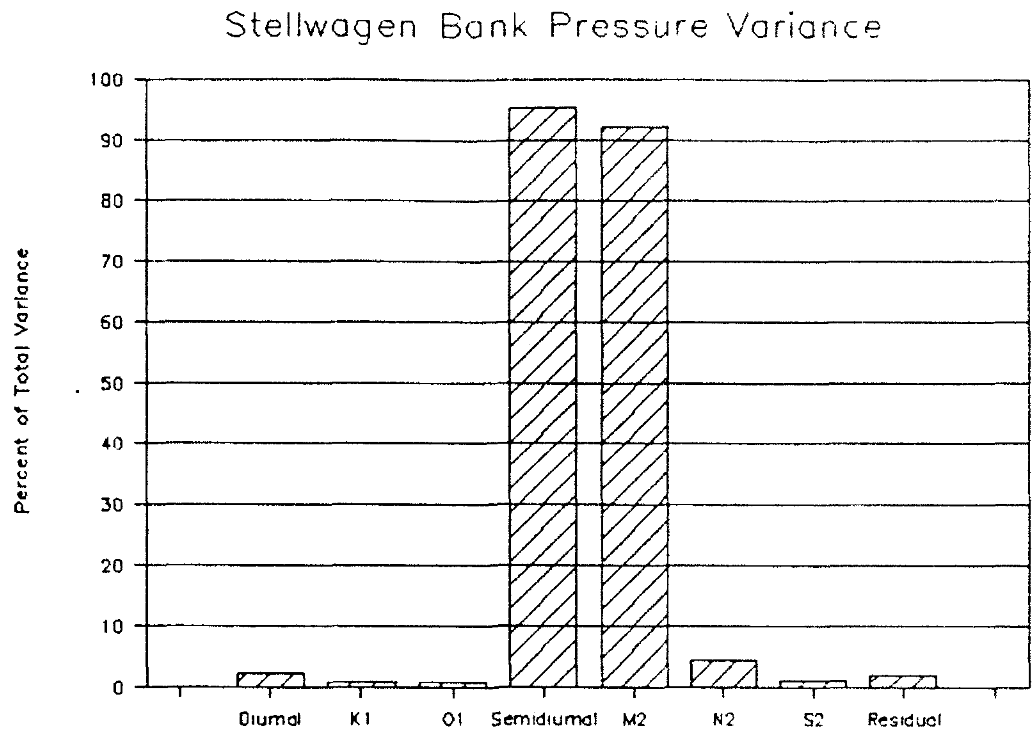


Figure 6. The admittance function at cycle per month intervals, relating the gravitational potential forcing function (Munk and Cartwright, 1966) to the observed Stellwagen Basin Pressure (converted to cm elevation), is shown for the diurnal and semidiurnal tides. The admittance is plotted as an amplitude gain (top) and phase shift (bottom). The amplification due to the Gulf of Maine/Bay of Fundy resonance is evident in the semidiurnal tidal band.



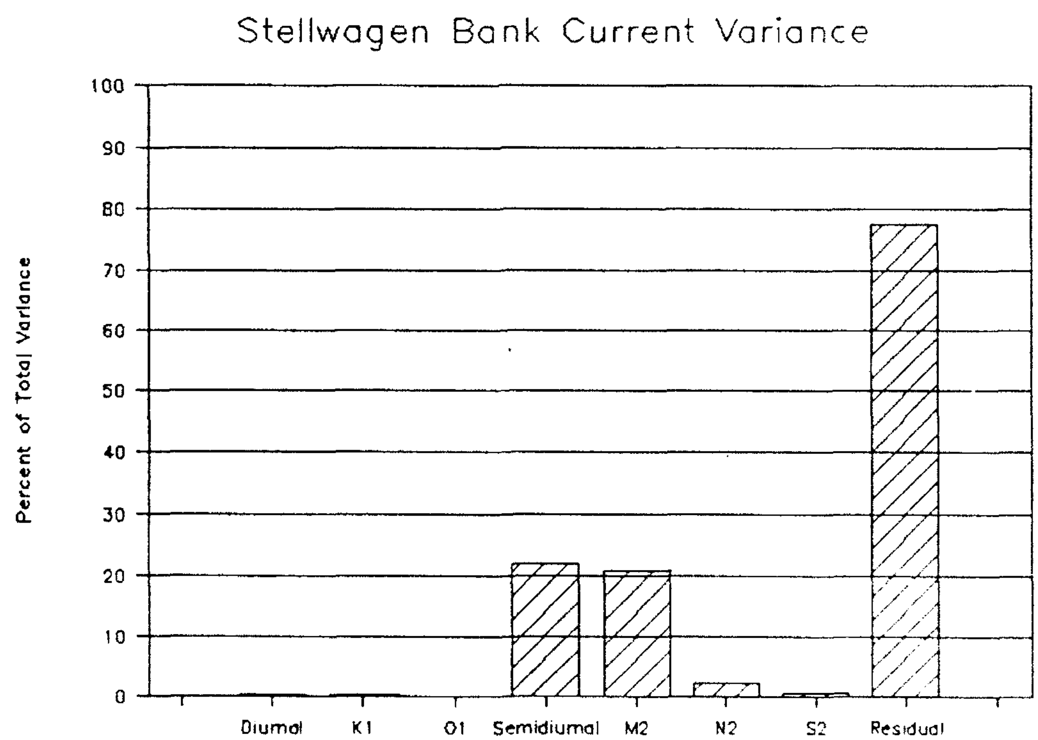


Figure 7. The pressure variance (top) and current variance (bottom) on Stellwagen Bank is divided to show how much is predicted in the diurnal and semidiurnal bands and how much is remaining as a non-predicted residual. The contributions to the predicted variance by the K1, O1, N2, M2 and S2 tides are shown. The large amount of the variance not predicted in the current record (residual) is due to internal wave effects.

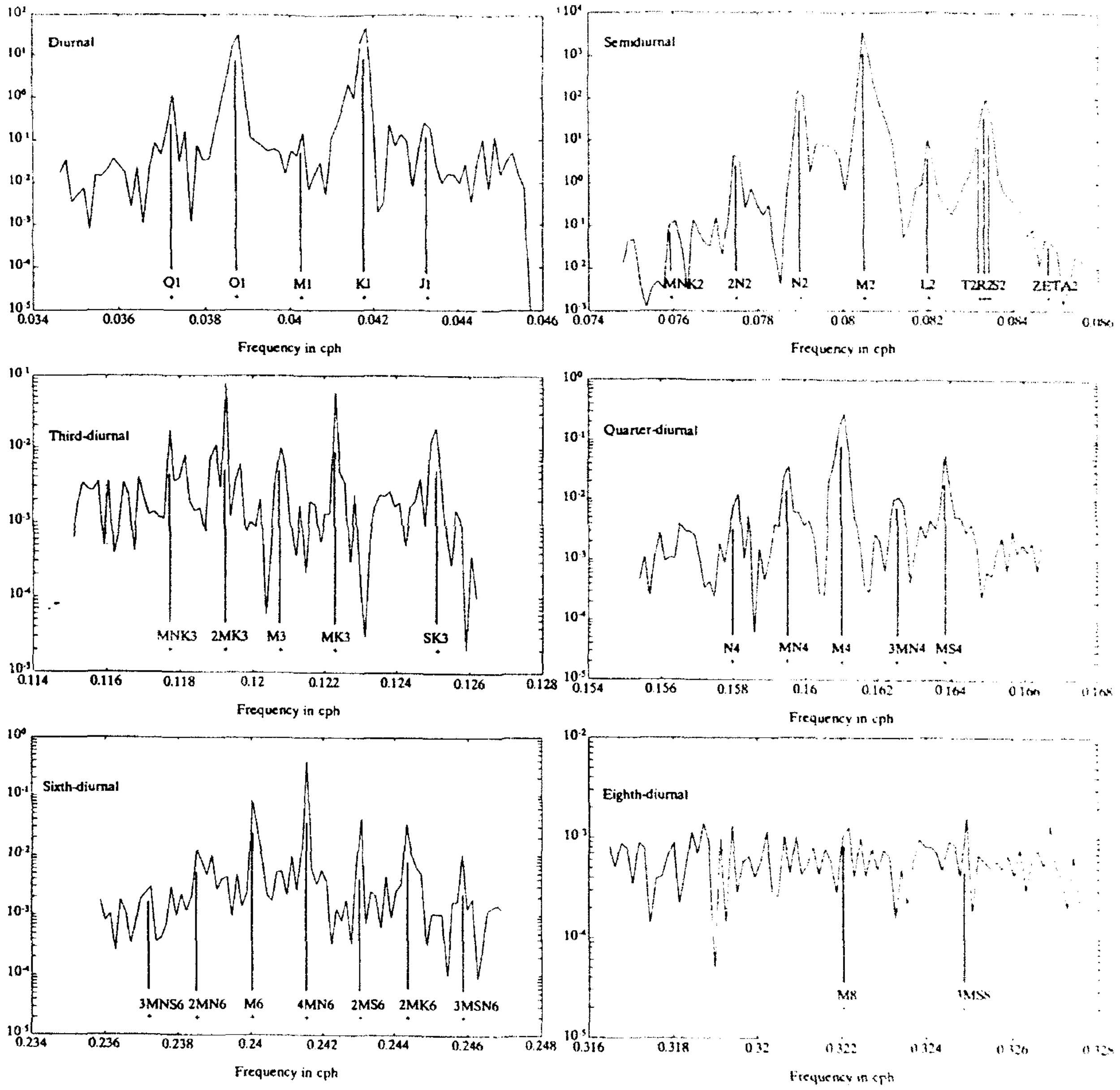


Figure 8. An expanded spectral presentation of the normal and higher harmonic or compound tides from the Stellwagen Pressure Record. The frequencies of the main constituents are marked with a vertical bar and named for reference.

shallow water effects. In large rivers this appears as a steepening of the flood over the ebb tidal elevation which increases as one goes upstream, e.g. the Delaware River and Bay (Parker, 1991). Since the tides are a sum of sine waves at specific frequencies, non-linear effects cause the transfer of energy into sine waves at the sum and difference frequencies. With the resonance in the Gulf, the N2 tide is amplified more than the M2, and compound tides involving the N2 line are more prevalent than seen in other localities (compare with results shown by Parker, 1991, LeProvost, 1991).

These non-linear interactions also produce frequencies in the diurnal and semidiurnal bands. The MNK2 line in the semidiurnal band is the result of the interaction of the M2, N2 and K1 frequencies (M2+N2-2*K1) to produce a frequency of 0.073949 cph. Non-linear interaction can also produce frequencies which fall at the same frequencies as linear tides. The 2ML2 line (not marked) is the interaction of the M2 and L2 frequencies (2*M2-L2) to produce a frequency of 0.078999, the same as the N2 tidal line. Thus, the analysis could be considerably complicated if all the possible non-linear interactions needed to be considered. In Massachusetts Bay, the M2 tide is so strong and dominant, that for all practical purposes the non-linear terms in the diurnal and semidiurnal frequency bands are negligible. Higher harmonics tides are produced by non-linear interactions such as the NMK3 tide (N2+M2-K1) which is not normally seen, but is important here because of the amplification of the N2 tide. Other higher frequency compound tides include the 3MN4 (3*M2-N2), 3MNS6 (3*M2 N2-S2) and 3MS8 (3*M2+S2). It is not clear that any eight-diurnal tides are statistically significant (see Figure 8).

A better understanding of the tides of the region and the response of the Gulf of Maine system might be obtained with a more detailed study of the cor ɔound tides in the Massachusetts Bay and the Gulf of Maine system. Understanding this ˛esponse may be important if Canadian tidal power plants were to be constructed across embayments in the Bay of Fundy. There is the possibility of changing the resonant frequency of the Gulf of Maine. By shortening the Gulf of Maine/Bay of Fundy system, the resonant frequency would be increased and become closer to the tidal forcing. Then semidiurnal tidal heights in the Bay of Fundy and Massachusetts Bay would be increased. Since the energy associated with these higher harmonics in the sea surface elevation records, is, again, quite small compared with the semidiurnal energy, further discussion is not warranted here. However, in the current records on Stellwagen Bank the compound tides are of the same amplitude as the diurnal currents (Figure 5), and if more detailed study of the tides is done beyond the semidiurnal (M2) analysis, the higher harmonics in the currents are the next order problem rather than the diurnal currents.

2.3 Harmonic Tidal Analysis of Massachusetts Bay Observations

Since there was no significant difference among the three methods of tidal analysis (except for the S2 response analysis), a harmonic analysis was done on all the observed pressures and elevation data for Massachusetts Bay. Pressures were analyzed as pressure records, and the results converted to elevation by multiplying by 99.55 cm/dbar. These results are tabulated for the 5 main diurnal and semidiurnal constituents in Table 3. Where there are several separate deployments with gaps of less than one month which make up an observation at one location, the individual sections were analyzed, then the records were joined together using a tidal prediction from the longest adjacent section to fill the gap to create one long record. The results from the analysis of the longest joined record is also shown. When the length exceeds one year, the first and last 365 days are analyzed and both results shown. Also, for comparison with this analysis, Table 4 lists other selected stations from Moody et al., (1984), and Irish (1990). Moody et al., (1984) also lists results for tidal

TABLE 3 - Tidal Constants for Massachusetts Bays
Harmonic Analysis of the Massachusetts Bays Program Pressure Observations. Amplitudes were multiplied by 99.55 to get cm)

Station & Section		Latitude Longitude	Record days	M2 H(cm) G(deg)	N2 H(cm) G(deg)	S2 H(cm) G(deg)	K1 H(cm) G(deg)	O1 H(cm) G(deg)	M4 H(cm) G(deg)	M6 H(cm) G(deg)
Prov-	1	41.9667	60	134.1	27.5	21.9	13.0	11.9	2.30	3.34
ince-		70.6633		112.2	75.4	146.3	201.7	192.7	1.5	293.4
town										
Coast	2		243	133.5	30.0	20.3	13.8	11.4	2.04	4.00
Guard				106.6	72.3	141.9	204.8	185.6	349.8	282.0
	3		186	132.4	30.5	21.4	14.5	11.4	1.82	3.58
				111.9	75.9	146.7	208.6	189.7	1.2	295.4
	YR1		365	133.3	29.9	21.0	13.8	11.4	1.99	3.92
				106.5	72.3	142.6	204.6	185.6	348.8	280.5
	YR2		365	131.9	30.4	20.3	13.6	11.1	1.75	3.50
				109.0	75.8	144.6	205.9	186.0	354.0	283.3
Stell-	1	42.3718	10	131.6	23.0	13.7	12.0	10.7	2.17	2.25
wagen		70.3483		108.1	81.9	148.3	217.0	163.1	331.9	320.5
Bank										
Bottom	2		171	122.4	27.9	17.0	13.8	10.8	1.30	0.96
Pressure				108.5	76.0	138.4	203.6	185.1	339.4	268.0
	3		102	122.8	27.4	19.4	14.7	10.9	0.98	0.89
				107.6	71.3	141.9	204.1	190.9	333.1	270.9
	Sum		300	122.8	27.2	18.9	13.8	10.8	1.26	1.07
				108.3	72.5	141.9	203.5	186.7	341.0	287.3
Stell-	1	42.3552	123	122.1	27.9	19.8	13.3	10.4	1.49	1.16
wagen		70.4002		105.8	72.9	137.2	202.0	183.1	351.8	263.5
Basin										
	2		67	123.1	27.2	19.7	14.9	11.6	1.26	0.91
				106.6	70.3	141.0	202.3	188.2	357.9	264.4
	Sum		207	122.2	27.9	21.9	13.4	10.7	1.40	1.14
				104.4	71.7	156.3	202.7	182.4	348.1	262.5
North		42.5223	138	122.8	28.6	18.6	13.2	11.3	1.22	0.60
Channel		70.4877		113.0	71.2	148.4	206.7	191.2	3.1	275.7
Glouc-	1	42.0617	47	129.0	27.6	21.6	13.5	12.0	1.99	1.25
ester		70.2433		107.0	66.8	139.5	200.9	191.8	356.7	255.2
Coast										
Guard	2		83	126.9	27.7	17.4	14.6	10.9	1.49	1.11
Station				108.2	74.2	150.4	210.0	183.5	350.2	268.8
	3		204	126.1	28.3	18.1	13.9	11.1	1.40	0.97
				106.4	72.0	147.4	205.6	185.1	347.8	258.6
	2&3		288	126.5	28.6	19.7	13.5	10.9	1.38	1.07
				106.8	72.8	142.6	204.8	183.7	347.8	258.1

TABLE 3 cont. - Harmonic Tidal Constants f[illegible] Massachusetts Bays

Station & Section		Latitude Longitude	Record days	M2 H(cm) G(deg)	N2 H(cm) G(deg)	S2 H(cm) G(deg)	K1 H(cm) G(deg)	O1 H(cm) G(deg)	M4 H(cm) G(deg)	M6 H(cm) G(deg)
Boston	1	42.3767	50	129.6	28.6	18.9	13.8	11.5	1.41	1.64
Light Buoy		70.7817		108.4	85.5	144.6	207.1	188.2	0.8	285.5
Bottom	2		109	127.0	28.5	20.0	14.1	11.2	1.29	1.46
Pressure				105.6	72.1	140.1	207.8	184.1	339.2	256.4
Boston		42.35	365	135.4	30.3	20.8	14.0	11.1	2.00	3.19
Sea Level		70.05		109.8	76.6	147.8	206.8	184.9	20.4	280.4

TABLE 4 - Historic Harmonic Tidal Constants for the Gulf of Maine and Massachusetts Bay in order of decreasing importance.

From Moody et al. (1984): (Amplitudes reported in cm)

Station	Latitude Longitude	Record days	M2 H(cm) G(deg)	N2 H(cm) G(deg)	S2 H(cm) G(deg)	K1 H(cm) G(deg)	O1 H(cm) G(deg)
Nauset	41.82	58	103.2	22.2	14.4	13.1	11.5
	69.93		102.	70.	13[illegible].	201.	182.
Cape Cod	42.05	29	116.				
Light	70.08		113.				
Cape Cod	41.77	369	124.4	28.9	19.9	13.1	10.8
Canal	70.50		109.	74.	144.	206.	187.
Portsmouth	43.08	365	130.3	27.8	20.3	14.1	11.2
N.H.	70.73		107.	76.	143.	204.	185.
Portland	43.65	1845	133.0	29.6	21.7	13.9	11.1
Maine	70.25		103.	73.	138.	202.	183.
Cashes	43.18	57	120.0	28.2	19.5	12.5	10.1
Ledge	69.08		98.	66.	126.	198.	186.

From Irish (1990): (Amplitudes were reported in decibars and were multiplied by 99.55 to get the cm amplitudes tabulated here)

Station	Latitude Longitude	Record days	M2 H(cm) G(deg)	N2 H(cm) G(deg)	S2 H(cm) G(deg)	K1 H(cm) G(deg)	O1 H(cm) G(deg)	M4 H(cm) G(deg)	M6 H(cm) G(deg)
Wilkinson	42.515	80	111.0	25.3	24.1	12.4	10.0	0.84	0.14
Basin	69.483		94.0	63.4	140.5	200.2	182.5	340.2	117.4
Georges	42.523	391	81.1	18.1	16.6	10.8	8.6	0.47	0.56
Basin	67.215		77.7	50.5	113.1	191.5	179.0	94.0	8.7

analyses for stations located along the coast and shelf from the Mid-Atlantic Bight up into the Canadian Maritime Provinces.

The results of the Massachusetts Bay tidal analysis are summarized on cotidal charts in Figures 9 (O1), 10 (K1), 11 (N2), 12 (M2), 13 (S2), 14 (M4) and 15 (M6) which show the spatial variation in the amplitude and phase for each constituent. In Massachusetts Bay, the water level appears to rise and fall uniformly with nearly the same amplitude at nearly the same phase for the diurnal and semidiurnal constituents. There is a slight amplification and phase lag in Boston harbor and a small amplification in Provincetown, probably associated with the location of the pressure gauge behind the tip of Cape Cod at the Coast Guard station. To within 15 minutes in phase and a few percent in amplitude, the surface elevation in Massachusetts Bay can be considered to rise and fall the same amplitude at constant phase for all the tidal constituents. The M4 and M6 charts have much larger uncertainties in the estimates, but do show a systematic amplification in Provincetown and Boston, and a phase consistent with wave propagation down from the north. However simple and uncomplicated the surface elevation looks, it is not reflected in the currents, which are subject to the effects of the bathymetry and presence of strong internal waves.

2. TIDAL CURRENTS:

2.1. Currents Driven by Surface Forcing and Bathymetry

The pressure gradient due to the rising and falling sea surface forces tidal currents which move at the same frequency, but whose behavior is also modified by the bathymetry, e.g. shallower water causing faster currents, or flow being directed along depth contours. Thinking of this another way, the water has to flow into Massachusetts Bay to cause the nearly simultaneous rise in sea level observed at the stations as shown in Figures 9 through 13. The total volume of the flow is well behaved, but the actual path of the currents and their velocity is controlled by the bathymetry.

2.2. Internal Tidal Contamination of Current Records

The analysis of the currents for their tidal content can be complicated by the presence of internal waves. These waves are generated by the tidal currents flowing over topography, but propagate as internal waves with characteristics controlled by the density structure of the water column. They are generated with a fixed-phase relationship to the surface tide at the generation site, and therefore are hard to separate from the currents directly associated with the surface or barotropic tides. To the first order they do not show up in the pressure or sea surface records, since there is little surface elevation, the maximum elevation occurring somewhere in mid-water column, depending on the density stratification. However, internal waves do have a strong current component, especially at the surface and bottom, which makes tidal analysis more difficult.

The tidal currents that are directly attributed to the barotropic or surface tide can be predicted by standard tidal theory once a "proper" analysis is completed. But tidal theory does not allow prediction of the amplitude and phase of the internal tide, and our normal tidal analysis techniques do a poor job of separating the barotropic part of the currents from the baroclinic or internal wave part. The amplitude and phase of the internal tide changes with season as the water stratification changes, since it is the vertical density gradient which controls the speed and propagation of the internal tides. Because of this, there may be some chance of separating the two components by using long records and looking at the part of the signal that has a single amplitude and phase relationship over the entire record length

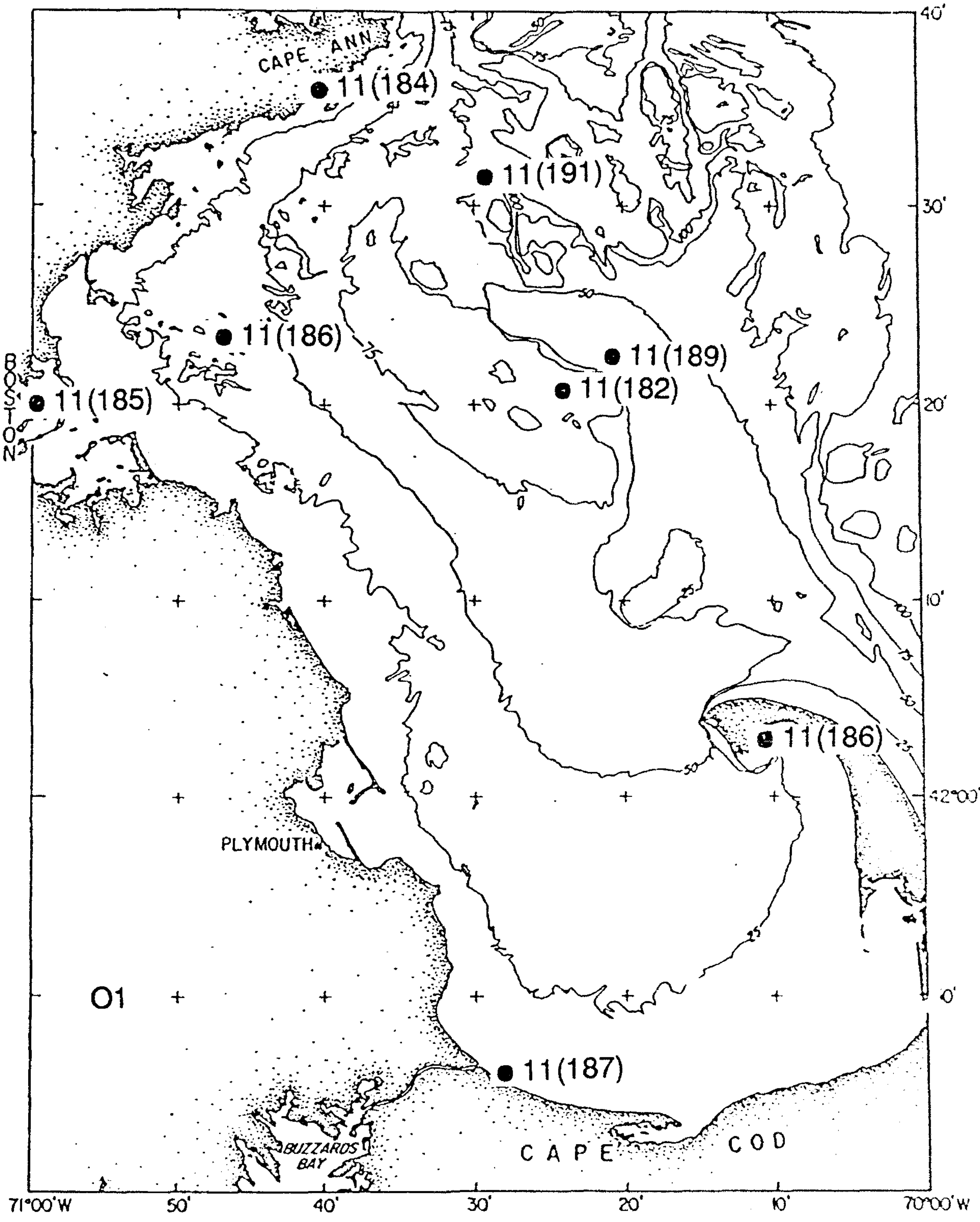


Figure 9. A cotidal chart of the O1 constituent of the tide shows the tidal elevation in cm and phase in Greenwich Epoch in parentheses for the stations tabulated in Tables 3 and 4. Uncertainties in the amplitude and phase estimates are about ±0.2 cm and ±1 degree depending on the record length.

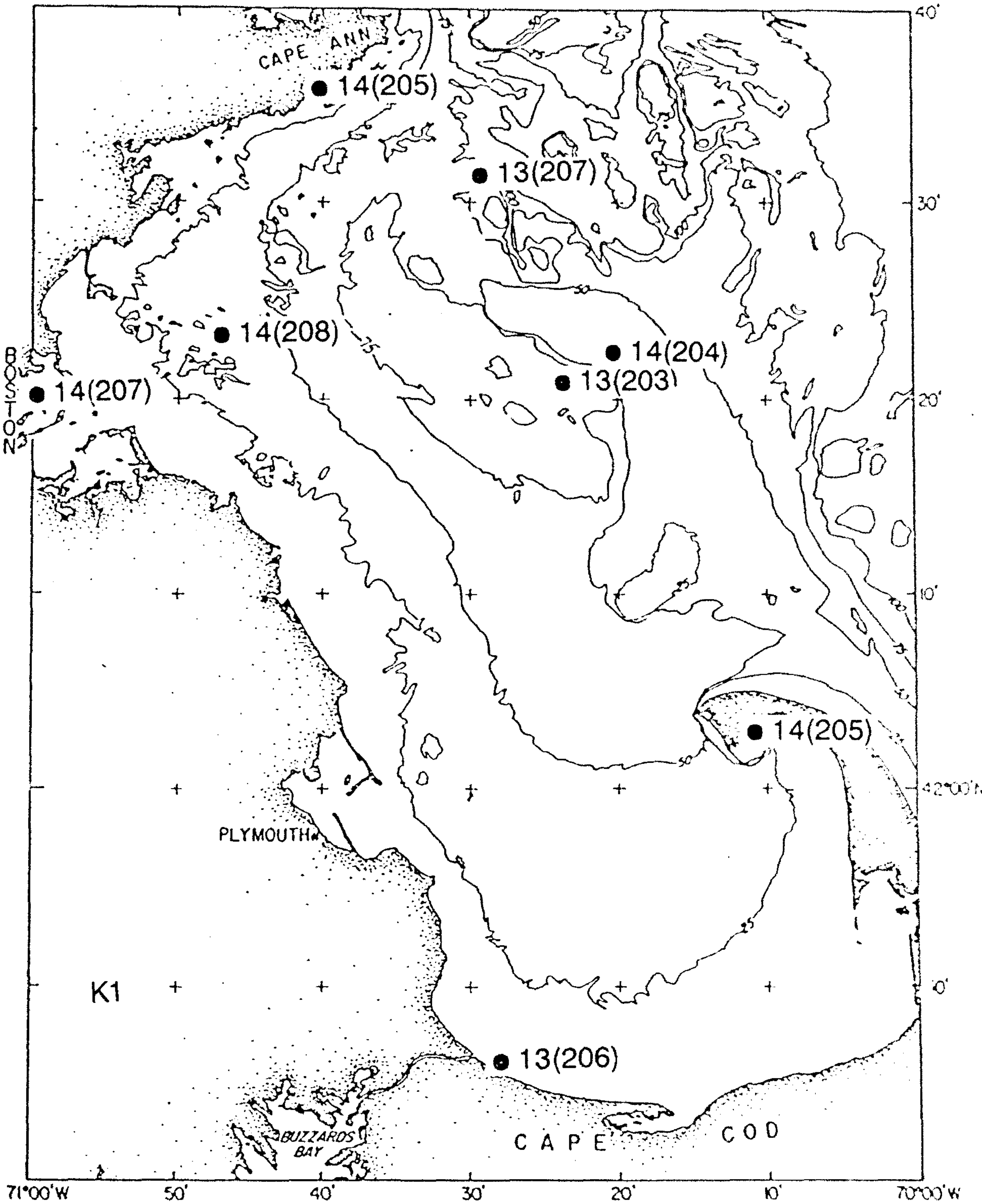


Figure 10. A cotidal chart of the K1 constituent of the tide shows the tidal elevation in cm and phase in Greenwich Epoch in parentheses for the stations tabulated in Tables 3 and 4. Uncertainties in the amplitude and phase estimates are about ±0.2 cm and ± 1 degree depending on the record length.

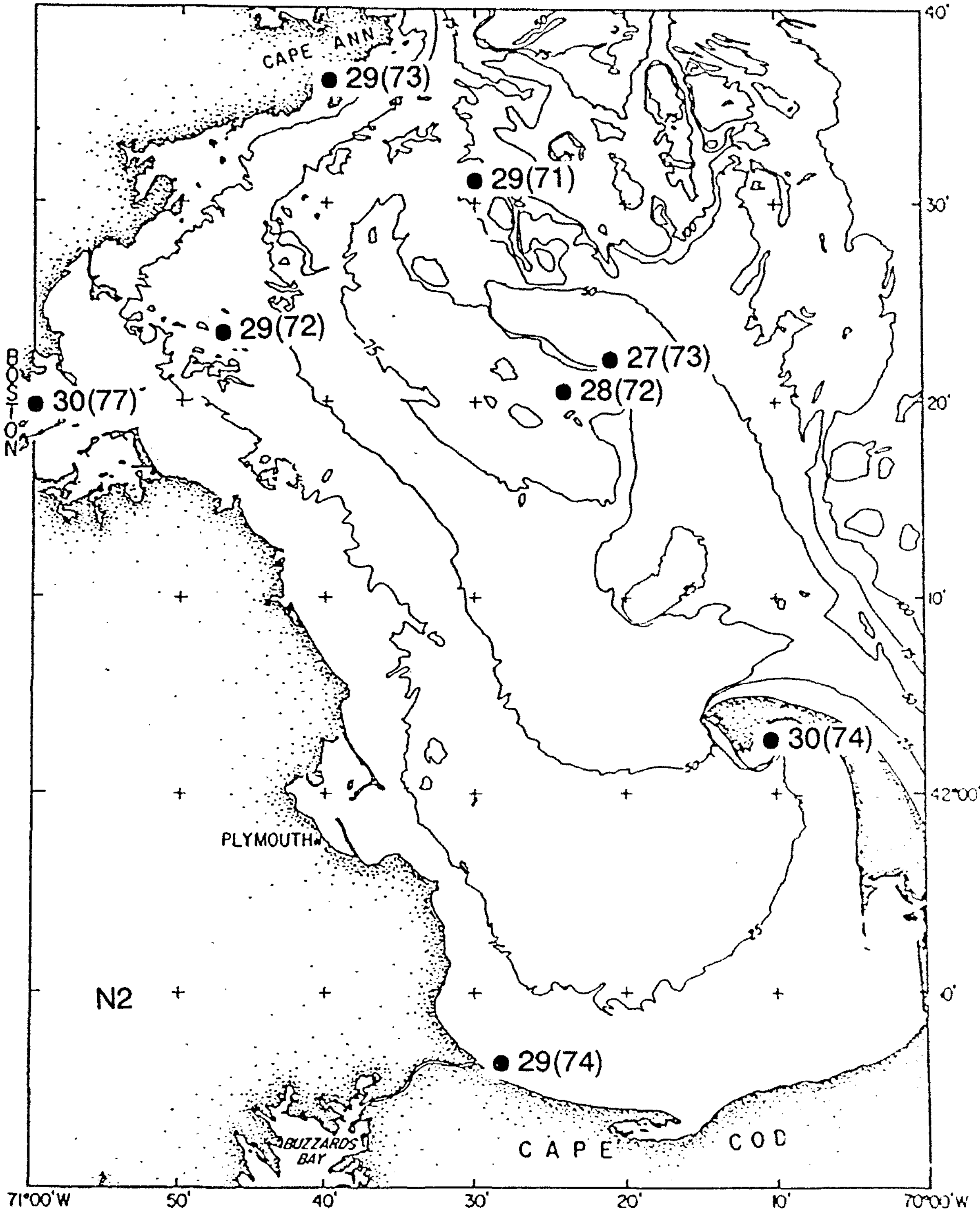


Figure 11. A cotidal chart of the N2 constituent of the tide shows the tidal elevation in cm and phase in Greenwich Epoch in parentheses for the stations tabulated in Tables 3 and 4. Uncertainties in the amplitude and phase estimates are about ±0.2 cm and ± 1 degree depending on the record length.

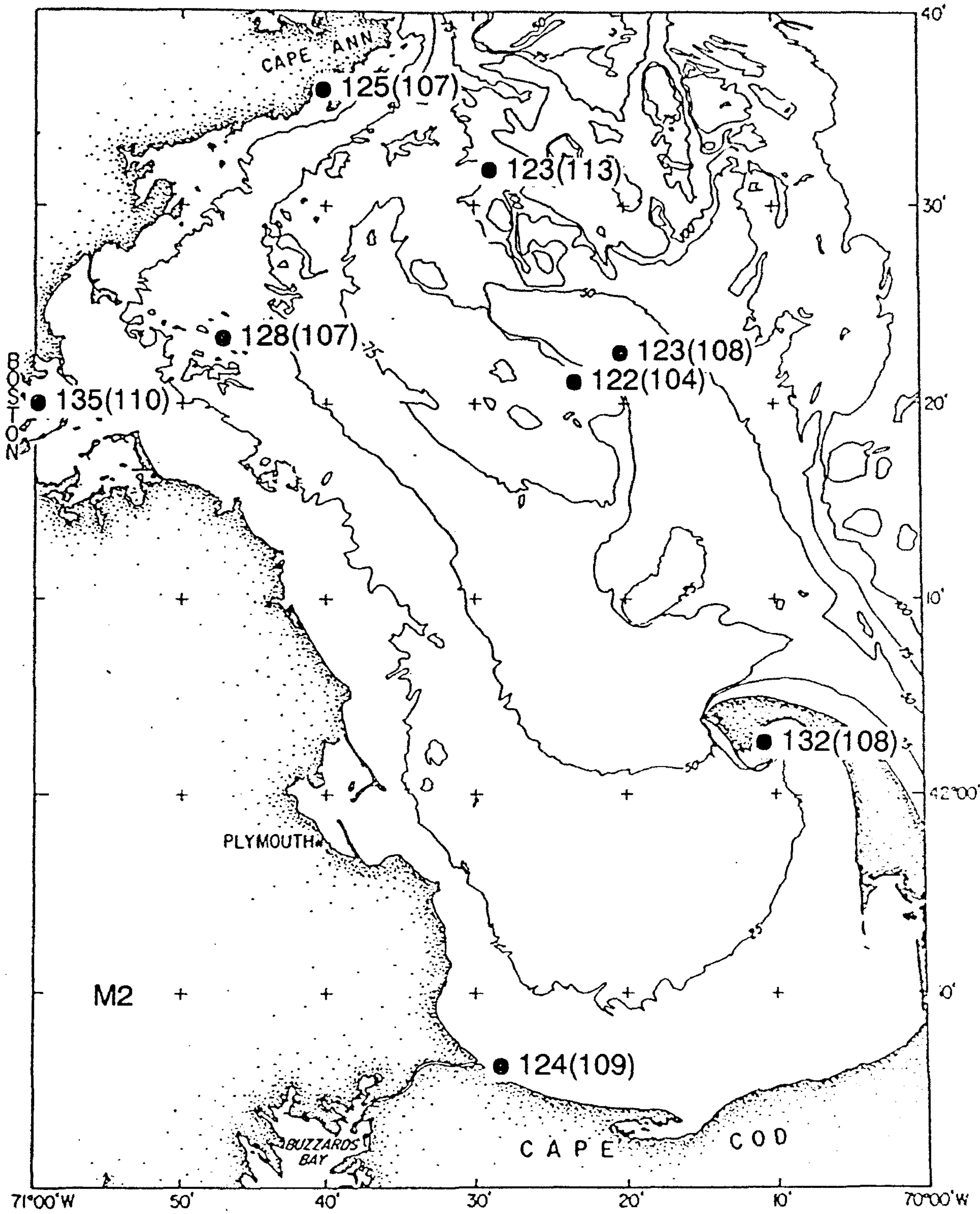


Figure 12. A cotidal chart of the M2 constituent of the tide shows the tidal elevation in cm and phase in Greenwich Epoch in parentheses for the stations tabulated in Tables 3 and 4. Uncertainties in the amplitude and phase estimates are about ±0.2 cm and ±0.2 degree depending on the record length.

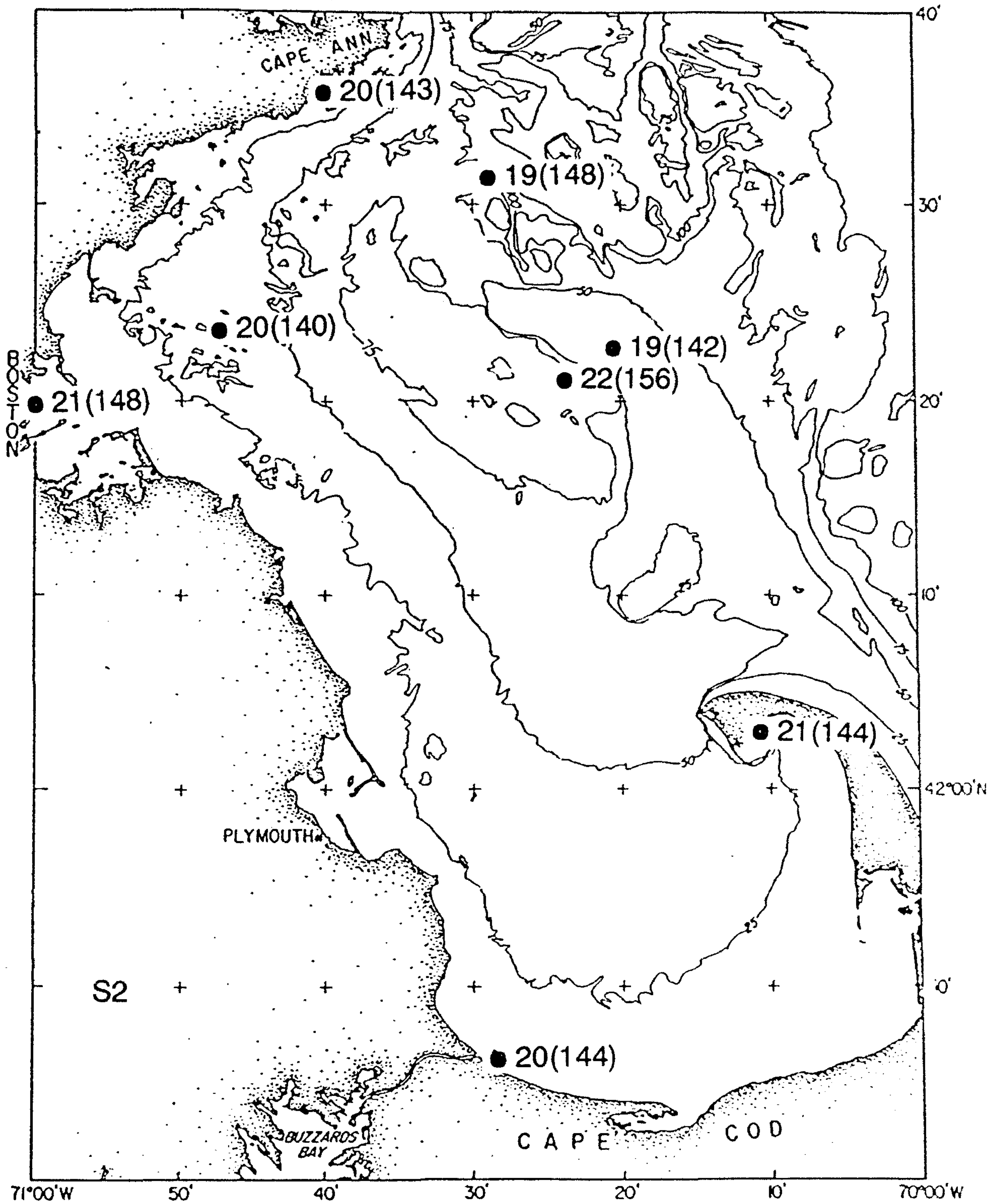


Figure 13. A cotidal chart of the S2 constituent of the tide shows the tidal elevation in cm and phase in Greenwich Epoch in parentheses for the stations tabulated in Tables 3 and 4. Uncertainties in the amplitude and phase estimates are about ± 1.0 cm and ±2.0 degree depending on the record length .

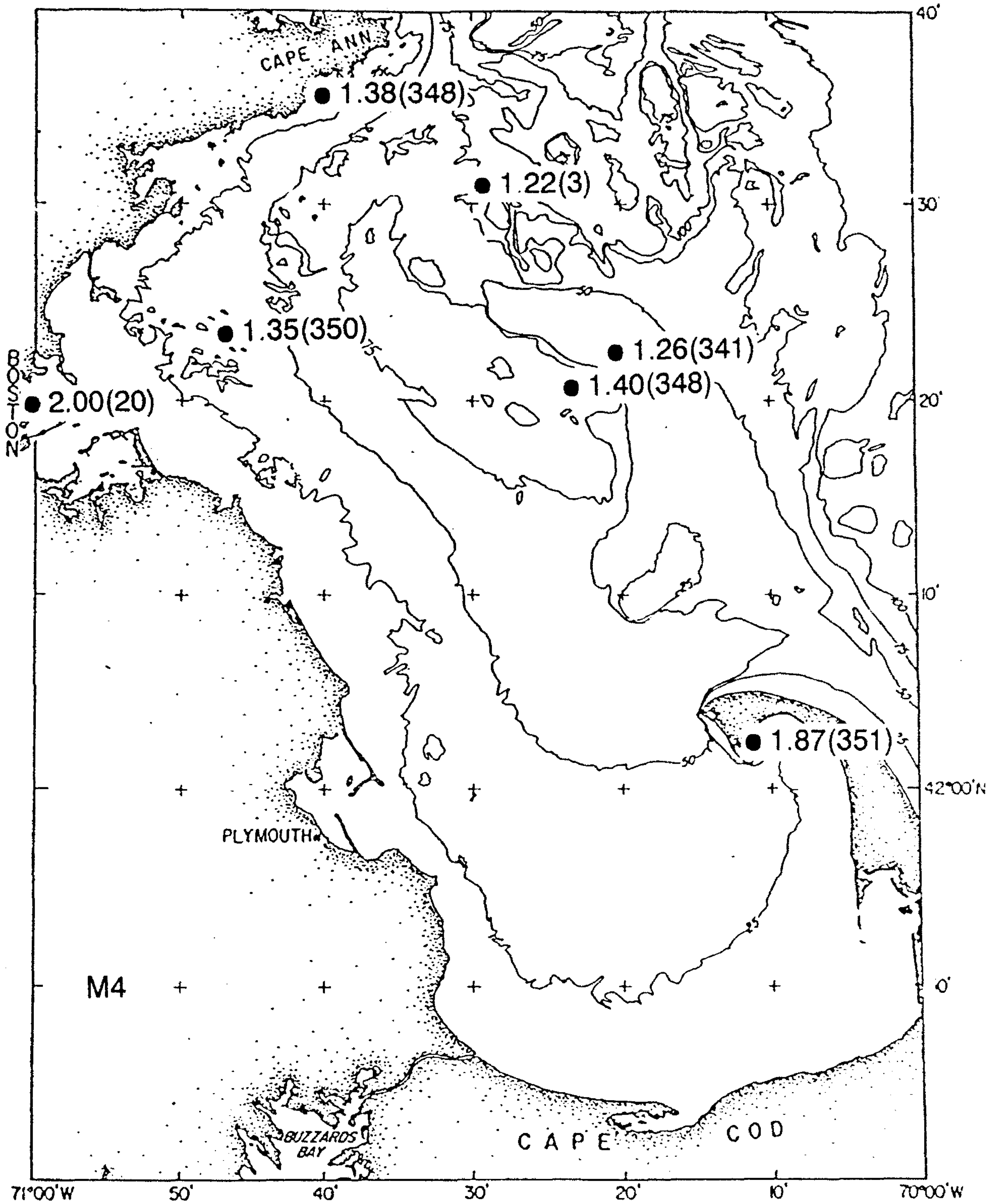


Figure 14. A cotidal chart of the M4 constituent of the tide shows the tidal elevation in cm and phase in Greenwich Epoch in parentheses for the stations tabulated in Tables 3 and 4.

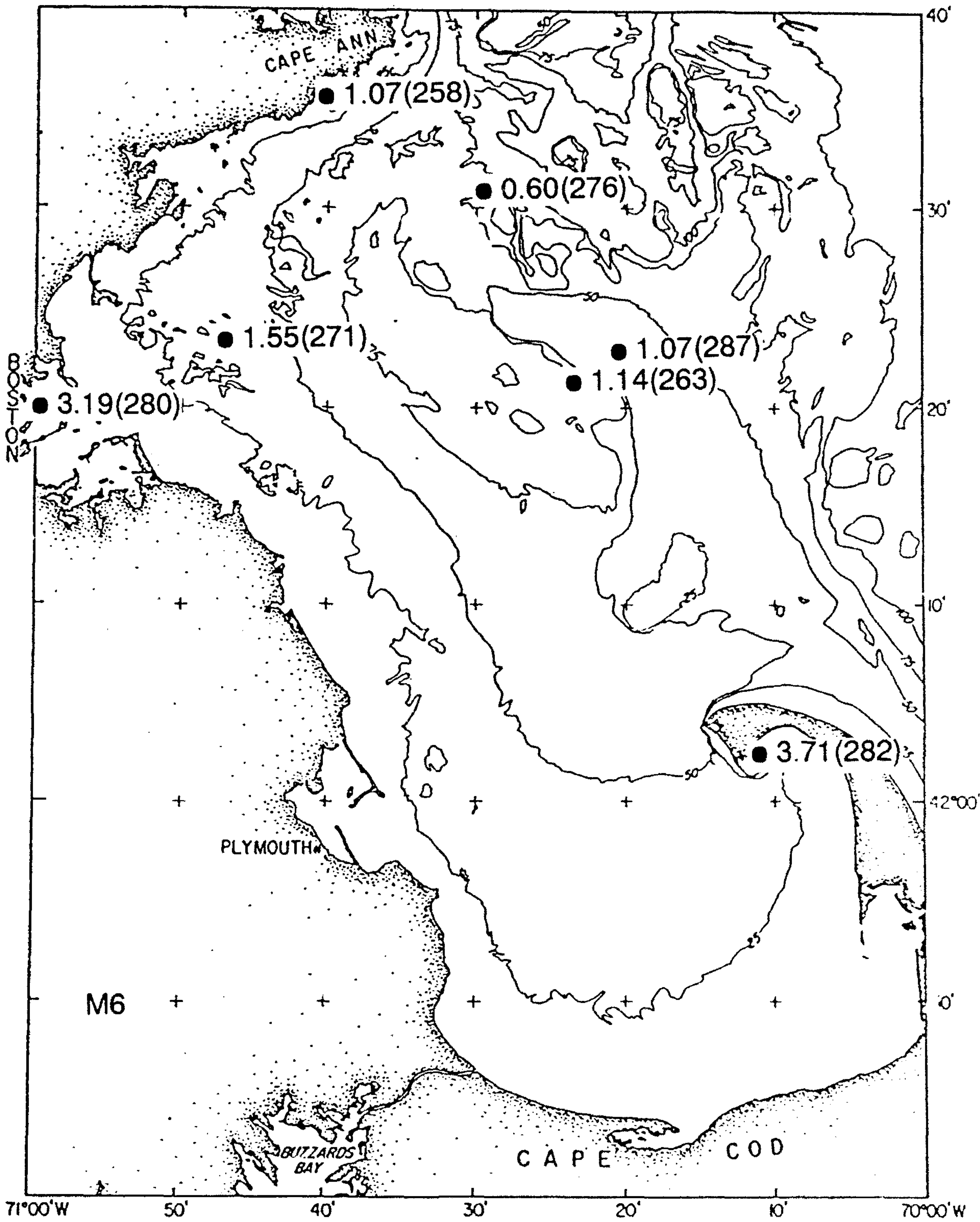


Figure 15. A cotidal chart of the M6 constituent of the tide shows the tidal elevation in cm and phase in Greenwich Epoch in parentheses for the stations tabulated in Tables 3 and 4.

with changing season. This technique may also work because the longer record gives a better frequency resolution and the internal tides are "broad-banded" by the changing density field, so they can be separated out by an analysis for line frequencies. Therefore, the discussion of the currents in this section must consider the internal wave energy which is examined in more detail at the Stellwagen Basin mooring in the next section.

Another way to minimize the effects of internal waves is to analyze the records for their tidal content during the winter when the water column in Massachusetts Bay is well mixed, since internal waves can only exist when there is a density stratification. A tidal analysis done during the winter months (November to March) when the water column is well mixed should represent the surface or barotropic tidal component in the velocity observations.

The spectrum of the bottom velocity at 27 meters depth over Stellwagen Bank (Figure 5), shows that the semidiurnal tidal currents dominate. The diurnal tidal currents are barely above background level, and about as strong as the higher harmonic or compound tides. The inertial currents (0.056 cph) can be seen in the spectrum, but are barely significant. Since this spectrum extends over nearly a year, it contains data when the internal tide is large and boosts the amplitude of the semidiurnal and higher frequency tides over the diurnal tides. There are no diurnal internal tides because free internal waves can not propagate at frequencies below the inertial frequency (0.056 cph). Therefore, the analysis can again concentrate on the M2 tidal currents as representative of the majority of the energy.

2.3. Tide Currents over Stellwagen Bank

The 300-day long current record from 27 meters depth on Stellwagen Bank was analyzed in detail to examine the sensitivity of the analysis techniques to contamination by the internal tide. Stellwagen Bank is a unique location as it is in the region of internal tidal generation, so may be the hardest record to separate the barotropic and baroclinic tides. The analysis of the single, long record was done by the three methods, as well as the winter time by the least squares technique only (because the data contained a substantial gap), to see if the modulation of the internal tide would separate the barotropic and baroclinic portions. The results of this comparison are listed in Table 5. Generally the three methods give similar results for the 300-day record, but definitely do not agree as well as they did for surface tidal elevations (see Table 1). The winter least squares analysis predicts greater amplitudes for the semidiurnal and higher frequencies and lower for the diurnal. Again this shows that internal wave contamination is present in the winter in spite of the very low vertical stratification. Analysis of the full record length to separate the internal and surface tides might be better if the records were continuous. However, patching the records is time consuming, and there is always the potential of biasing the results with an improper patch.

From the harmonic analysis, the residual variance (that part not predicted by the tidal analysis) is 77.4% of the observed variance. The semidiurnal band has 75.4% of the observed variance, but analysis only predicts 21.9% of the variance in the semidiurnal band. The M2 constituent is 94.6% of the predicted tide in the semidiurnal band, but only 20.7% of the total variance. Currents are more difficult to analyze than pressure or tidal elevation because they are contaminated with a higher background or non-tidal internal wave signal. While in the deep ocean a tidal analysis can typically predict 2/3 of the variance, here the barotropic tide only accounts for 25% of the variance. The majority of the signal on Stellwagen Bank (and also in the deep Massachusetts and Cape Cod Bays) in the semidiurnal tidal band is due to internal tides, which, during the stratified seasons, can

TABLE 5 - Stellwagen Bank Bottom Currents at 27 meters depth (2 m above the bottom). Tidal Analysis Comparison from 300-day record for the 5 main tidal constituents. Gaps in the observed record were filled by a tidal prediction from a neighboring section as a "neutral patch".

Tide Line	Harmonic		Response		Least Squares		Least Squares (Winter Only)	
Darwin Symbol Freq.(cpd)	Major Minor	Phase Tilt	Major Minor	Phase Tilt	Major Minor	Phase Tilt	Major Minor	Phase Tilt
O1 0.929536	0.52 0.08	79.2 27.3	0.49 0.08	75.1 29.1	0.49 0.09	78.0 27.8	0.55 0.04	139.5 27.3
K1 1.002738	1.03 -0.08	110.1 31.5	0.99 -0.13	104.3 26.0	0.90 -0.13	114.3 33.3	0.81 -0.05	133.3 72.7
N2 1.895982	2.32 -0.21	227.5 63.4	2.48 -0.55	199.1 63.1	2.33 -0.25	235.7 65.6	3.40 -0.26	10.8 60.4
M2 1.932274	9.01 -0.90	293.0 55.5	8.90 -0.90	293.0 55.6	9.89 -0.59	296.2 56.7	13.92 -0.16	42.7 61.3
S2 2.000000	1.42 -0.11	318.1 53.4	2.10 -0.10	275.3 76.7	1.69 -0.19	330.7 57.0	2.86 -0.22	50.7 31.8
M4 3.864547	0.45 0.15	43.6 11.1	- -	- -	0.47 0.17	40.9 11.4	0.76 0.27	345.4 28.9
M6 5.864547	0.94 -0.06	187.6 39.6	- -	- -	1.12 -0.07	186.4 39.6	1.31 -0.12	251.4 34.5

Major and Minor are amplitudes of the tidal ellipse in cm/sec.
If the minor axis is negative, then the current rotation is clockwise.
Phase is relative to Greenwich of the Maximum axis in the upper sector.
Tilt is the orientation of the maximum velocity axis clockwise from the north or vertical.
Winter Only is a least squares analysis for 1 November 1990 through 1 March 1991.

dominate the velocity observation. This is shown in Figure 7 and illustrates the difference between tidal elevations and current analysis with internal wave contamination.

2.4 Winter Least Squares Analysis for the Barotropic Tidal Currents

Since internal waves can only exist in the presence of a density stratification, an analysis of the records during the winter time, i.e. November 1990 through March 1991, when the water column in Stellwagen Basin was observed to be nearly homogeneous, should minimize the contamination due to internal tide energy. The "Winter Only" least squares analysis on the right of Table 5 uses just the winter section (1 November 1990 to 1 March 1991) for the analysis and, if anything, predicts more of the variance than the three methods for the entire record with "neutral" patches for the missing data. However, the least squares technique is mechanically much easier to apply to the winter part of the record because of the complications caused by the gap in the data due to mooring servicing and repair. The harmonic and response analysis of the 300-day record relied on filling the gap with a neutral patch. For the winter record the patch is a minimum of 13% of the record and can be as great as 43%. Therefore, the least squares technique was applied to the winter period to analyze for the tidal velocities, and to represent the currents with the least internal tide effects. The results for only the M2 constituent are given in Table 6, and summarized as current ellipses for the surface (4 to 8 meter depth records) velocity records in Figure 16.

The tidal analysis programs analyze the East and North velocity components separately, and then convert the results to an elliptical representation of the currents. Thus the two amplitudes and phases are represented as the amplitude of the major (maximum) axis and the amplitude of the minor (minimum) axis. The sign of the minor axis indicates the direction of the current vector rotation. A positive minor axis implies counterclockwise rotation, and a negative minor axis implies clockwise rotation. The phases become the tilt of the major axis from North, with positive angle being clockwise rotation. The Greenwich phase remains a Greenwich phase, but is now the phase of the maximum velocity of the major axis in the upper sector (tilts between -90 and +90 degrees) following the convention of Butman (1975) and Moody et al. (1984).

2.5 Doppler Current Profiles in Stellwagen Basin

The mooring in Stellwagen Basin (Figure 17) had a 150 kHz solar-powered downward-looking Doppler acoustic profiler beneath the surface buoy. The profiler recorded 4.3 meter vertical averages of currents at 17 vertical depths from 8.3 meters through 77.8 meters below the surface. These records were analyzed by the harmonic method for their tidal content for the winter and the spring records and the results listed in Table 7. The top two sections of the table give the results for the two parts of the winter record. The second part is 42 days long (the first part was 32 days long) and was selected as representative of the barotropic tidal currents. The results are similar to the first part, so no patching was attempted. A patched record would probably give more stable, but not very different, results. These results are plotted in Figure 18 which shows the amplitude and phase of the two velocity components versus depth at the bottom, and a summary plot of all nine tidal ellipses at the top. The currents become more elliptical (less circular) and increase slightly in amplitude with depth. The orientation of the major axis remains nearly constant as does the Greenwich Phase. These results are as expected for barotropic currents without internal waves since currents under a long wave such as the tides should have a constant amplitude with depth, a single tilt and constant Greenwich phase. In regions of bathymetric changes, the amplitudes, tilt and phase will change with depth. In Figure 18 no turning is seen, and the velocity of the deepest depth is only showing a small

TABLE 6 - Massachusetts Bay Currents Tidal Analysis of M2 Constituent for period from 1 November 1990 to 1 March 1991 by the least squares method. Results marked 1989 are from the same period in the previous year.

Station and Depth	Major cm/sec	Minor cm/sec	Tilt rel N	Phase in G	
Broad Sound @ 5 m	16.11	1.41	49.7	219.8	
Broad Sound @ 18 m	9.96	1.26	65.9	188.6	
Boston Buoy @ 5 m (1989)	9.43	-0.66	77.1	204.0	
Boston Buoy @ 5 m (1990)	9.85	-0.98	76.9	203.9	
Boston Buoy @ 23 m (1989)	9.10	-0.30	87.1	196.6	
Boston Buoy @ 23 m (1990)	7.71	0.55	-82.0	6.7	(Short)
Boston Buoy @ 33 m	6.69	0.59	77.0	185.1	
Manomet Point @ 5 m	11.26	0.03	-4.9	211.1	
Manomet Point @ 29 m	10.61	0.64	-1.3	207.3	
Race Point @ 05 m	40.81	3.28	54.3	200.2	
Race Point @ 23 m	43.47	-1.07	53.1	201.4	
Race Point @ 55 m	42.64	0.37	62.0	189.1	
Race Point @ 60 m	30.11	0.46	67.9	184.0	
Scituate @ 5 m	7.80	1.21	45.6	202.9	
Stellwagen Basin @ 75	13.49	0.88	-88.3	8.6	(Short)
Stellwagen Basin @ 84	7.94	1.64	-84.6	356.9	
North Channel @ 4 m	8.28	1.46	78.6	232.5	
North Channel @ 25 m	13.90	2.08	-89.5	50.1	
North Channel @ 60 m	11.21	2.86	84.3	237.4	
Stellwagen Bank @ 04 m	15.36	-1.27	68.6	231.7	
Stellwagen Bank @ 25	13.92	-0.16	61.3	42.7	
Cape Cod Bay @ 4 m	13.45	-0.24	-4.3	222.6	

If the minor axis is negative the current rotation is clockwise.
Tilt is the orientation of the maximum velocity axis clockwise from North.
Records labeled "short" are less than one month long

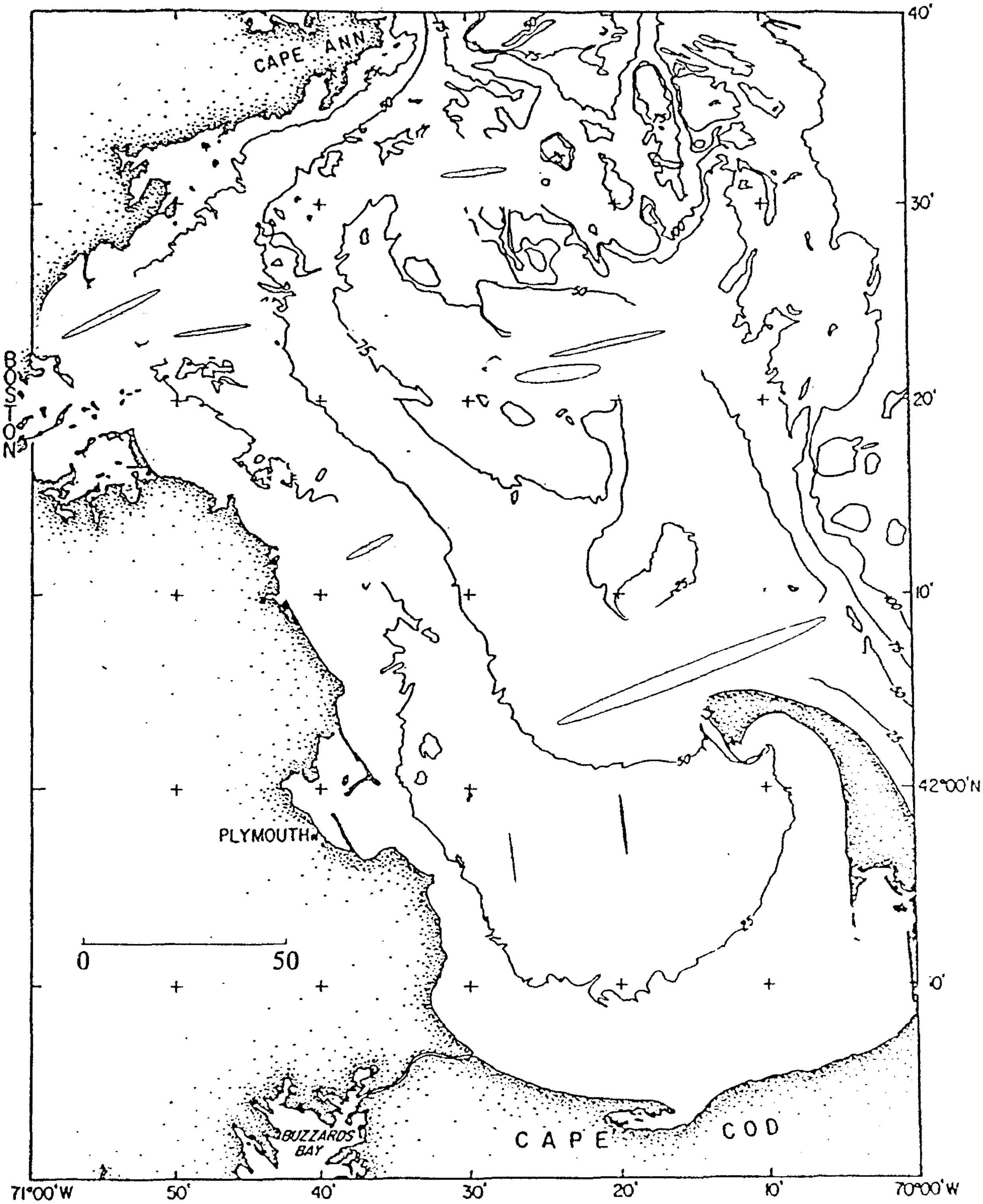


Figure 16. The current velocity ellipses from the surface (4 to 8 meters depth) for the winter analysis of the moorings (Table 6). The center of the ellipse is the mooring location. The scale for 50 cm/sec is shown on the lower left. The velocity ellipses are shown scaled to about 5 times the magnitude of the tidal excursion calculated by integrating the observed currents at the location.

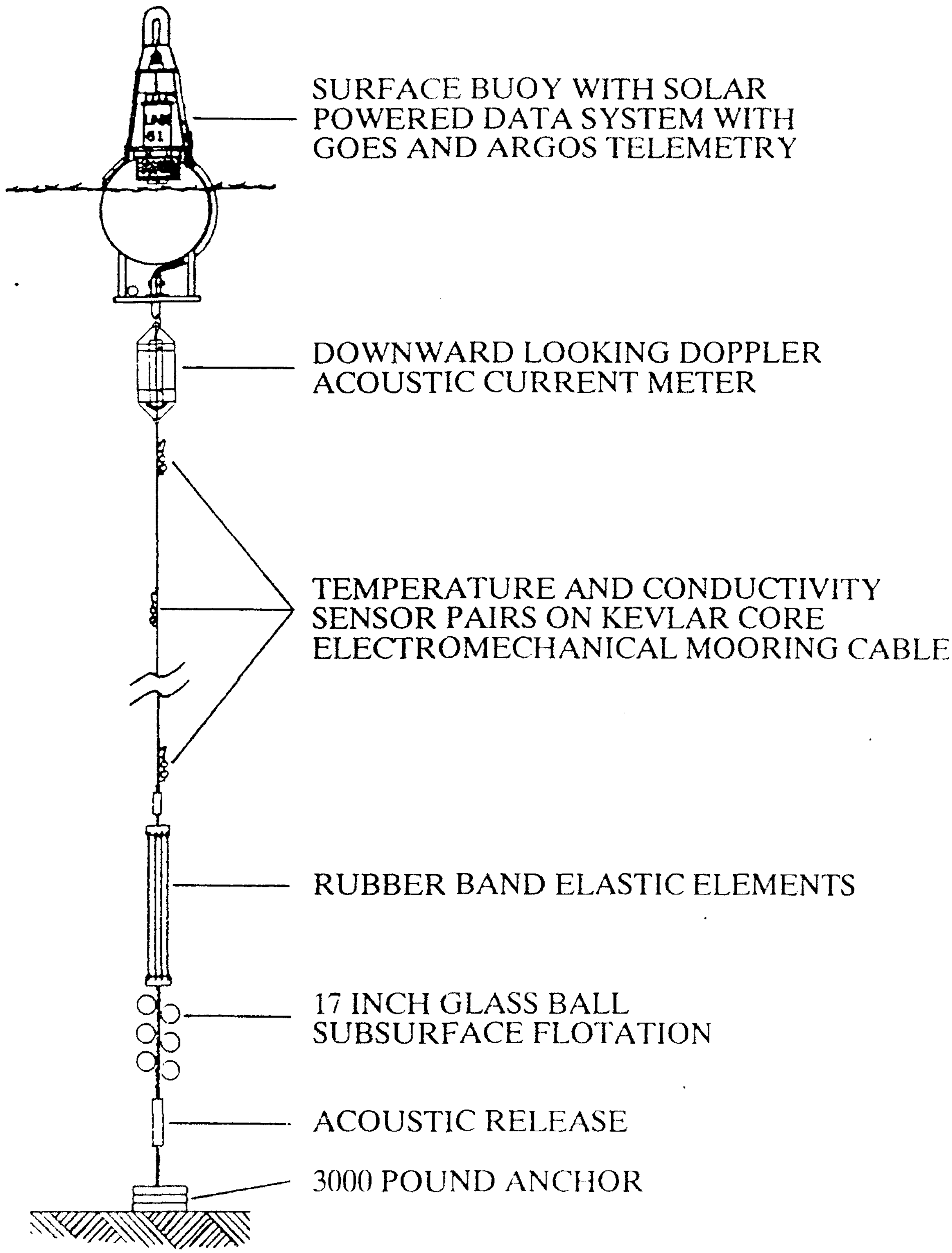


Figure 17. Stellwagen Basin Mooring Configuration. An acoustic Doppler current profiler measured 4.3 meter velocity bin averages from 8.3 m to 77.8 m, and temperature and conductivity were measured at 4, 10, 25, 45 and 60 meters depth.

TABLE 7 - Harmonic Analysis of the Stellwagen Basin Doppler Profiler Record for Tides and Internal Tides at the M2 Frequency

Winter Velocities, Part One - 8 November 1990 to 10 December 1990.

DEPTH meter	H cm/sec	G degree	H cm/sec	G degree	Major cm/sec	Minor cm/sec	Phase degree	Tilt degree
8.3	8.152	189.73	3.363	236.11	8.505	2.334	14.6	72.8
17.0	10.234	189.89	3.938	237.59	10.598	2.813	14.1	74.4
25.7	10.844	188.69	4.029	239.23	11.167	3.021	12.7	75.6
34.4	11.006	189.03	4.107	237.84	11.359	2.995	13.0	75.1
43.1	11.091	189.02	4.033	236.19	11.448	2.865	12.8	75.2
51.7	11.697	188.59	3.885	228.48	12.087	2.411	11.6	75.1
60.4	12.635	188.55	3.786	224.42	13.013	2.154	10.9	76.0
69.1	13.652	187.70	3.255	213.62	13.965	1.391	8.9	77.8
77.8	12.785	184.18	3.114	209.97	13.092	1.323	5.5	77.5

Winter Velocities, Part Two - 1 February 1991 to 15 March 1991.

	Eastgoing		Northgoing		Ellipse			
DEPTH meter	H cm/sec	G degree	H cm/sec	G degree	Major cm/sec	Minor cm/sec	Phase degree	Tilt degree
8.3	10.535	188.74	4.151	246.18	10.797	3.414	13.0	76.7
17.0	10.873	188.61	4.380	246.44	11.150	3.615	13.1	76.4
25.7	11.187	189.59	4.391	243.90	11.507	3.467	14.0	75.8
34.4	11.702	189.93	4.273	237.89	12.072	3.077	13.8	75.3
43.1	12.149	190.83	4.209	230.48	12.593	2.591	14.1	74.4
51.7	12.605	192.39	4.390	224.38	13.161	2.227	15.3	73.0
60.4	13.305	193.86	4.610	216.54	13.979	1.692	16.1	72.0
69.1	13.967	193.85	4.649	211.07	14.662	1.312	15.5	72.2
77.8	13.627	189.81	4.310	210.30	14.220	1.446	11.6	73.3

Spring Velocities - 15 March 1991 to 18 June 1991.

DEPTH meter	H cm/sec	G degree	H cm/sec	G degree	Major cm/sec	Minor cm/sec	Phase degree	Tilt degree
8.3	9.492	217.73	9.567	231.19	13.384	1.579	44.5	44.8
17.0	8.302	214.57	10.386	237.21	13.051	2.543	48.5	38.1
25.7	8.038	200.35	8.429	247.71	10.669	4.671	45.5	43.0
34.4	9.340	191.74	6.436	252.89	10.065	5.231	25.9	64.2
43.1	11.441	188.62	4.590	254.92	11.611	4.142	12.4	79.5
51.7	13.878	186.10	2.651	247.35	13.938	2.314	7.0	84.6
60.4	15.894	183.63	1.028	204.08	15.923	0.358	3.7	86.5
69.1	16.825	178.77	1.229	85.43	16.825	-1.227	178.8	-89.8
77.8	16.269	171.46	1.840	35.39	16.323	-1.272	171.8	-85.3

Spring Internal Tides - 15 Mar - 18 June 1991.

DEPTH meter	H cm/sec	G degree	H cm/sec	G degree	Major cm/sec	Minor cm/sec	Phase degree	Tilt degree
8.3	5.091	304.01	5.682	220.09	5.790	-4.968	59.1	21.9
17.0	4.963	321.42	6.125	230.45	6.126	-4.961	48.6	-2.3
25.7	3.589	344.75	4.063	251.80	4.081	-3.568	61.9	-11.2
34.4	2.336	3.03	2.557	278.69	2.607	-2.280	119.7	23.7
43.1	0.787	46.99	1.886	321.60	1.887	-0.784	142.4	2.3
51.7	1.955	141.61	2.176	16.28	2.604	-1.333	173.2	-39.7
60.4	3.688	143.96	3.590	40.13	4.054	-3.172	178.9	-48.2
69.1	4.976	131.85	5.428	41.79	5.428	-4.976	41.5	-0.3
77.8	5.467	119.88	6.110	31.82	6.124	-5.452	39.4	8.5

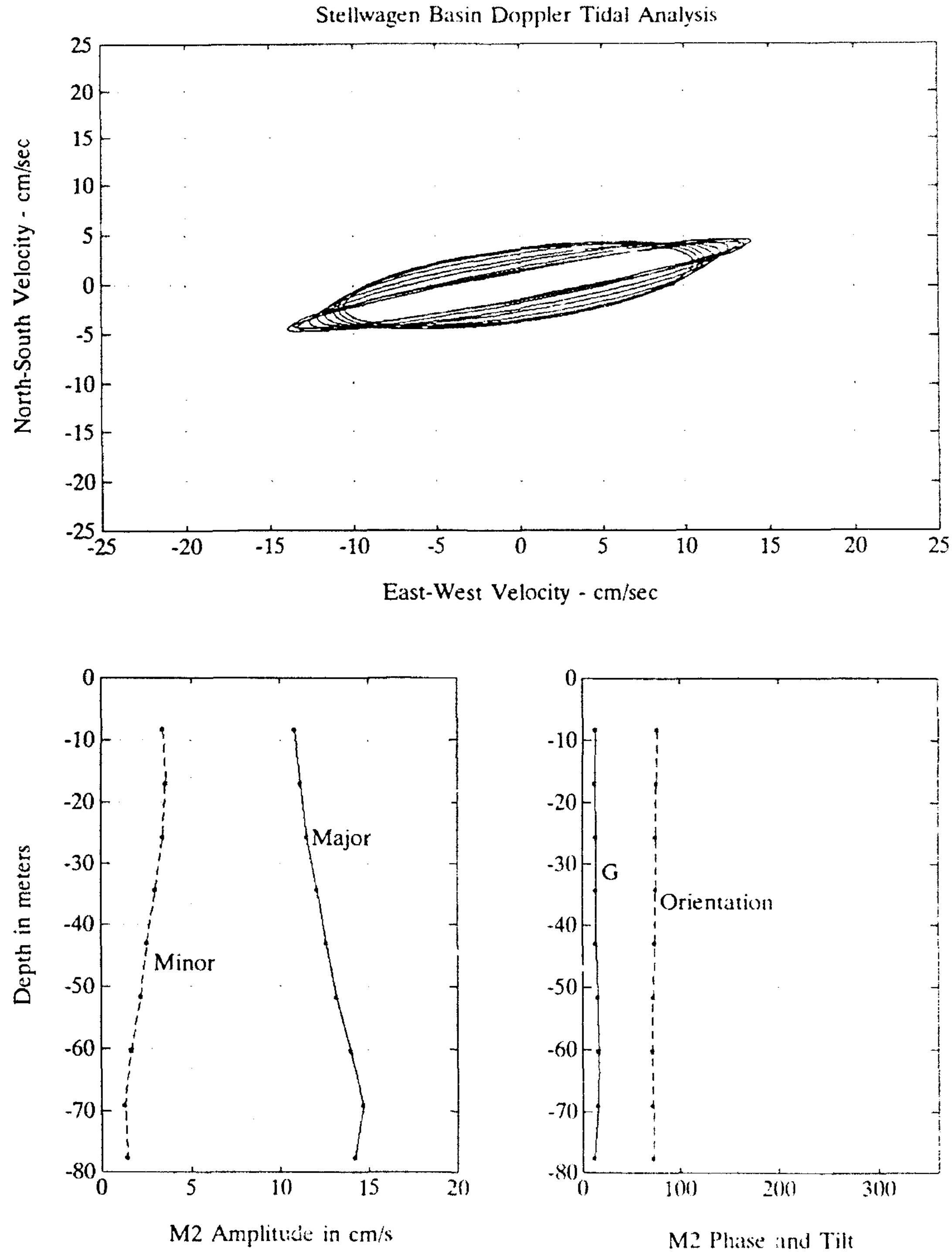


Figure 18. Winter 1991 (1 February to 15 March 1991) Stellwagen Basin Doppler profiler tidal analysis at the M2 frequency. The top panel shows the velocity ellipses (from Table 7 part two) with the smaller amplitude, and rounder ellipses at the surface and a steady increase in major axis amplitude, and decrease in minor axis amplitude with depth. There is no significant turning of the ellipse. The two amplitude components (Major axis solid and Minor axis dashed) and phase profiles (Greenwich phase solid and ellipse tilt dashed) are shown at the bottom. The currents are nearly barotropic.

effect of the bottom boundary layer reducing the amplitude. The result is a current which is nearly the same amplitude from the top to the bottom of the water column.

2.6 Analysis of Winter Records for the Tides

The tidal analysis of the winter data from Table 6 and Table 7 is summarized in Figure 16 for the surface currents at 4 to 8 meters depth. The depth dependence is illustrated in the more complicated Figure 19. The tidal ellipses from the various depths at a station are stacked one above the other with the shallowest on top. The whole stack is located roughly where the mooring is located, except for the Stellwagen Basin mooring whose profile is shown on the left with an arrow locating where it should be positioned. To the first order there is little change in the currents with depth, and the currents are nearly back and forth motion in a very elliptical manner. (The 75 and 84 meter deep records in Stellwagen Basin were taken with USGS VACMs, and the systematic difference in direction between the ADCP and VACM currents is being further examined elsewhere.) Therefore, we believe that it is a good representation of the barotropic component or that part of the tide that can be predicted for other times using harmonic tidal theory because it has little contamination with the internal tide. However, there is still some energy remaining in the tidal frequency band which is related to the internal tide. Also, additional tidal analyses for other constituents and time periods are included in the internal tide section because they are contaminated with the internal tidal effects and therefore are difficult to interpret as tidal currents.

The strongest tidal currents are seen in the South Channel between Race Point and Stellwagen Bank. M2 tidal currents exceed 40 cm/sec at all depths (except the tripod data in the boundary layer very near the bottom). This strong flow is due to the large amount of water that moves into and out of Cape Cod Bay with the changing tide level. The currents in the North Channel are typically 12 cm/sec, and less than 1/3 those in the South Channel. There is less volume of water required to fill the tidal prism in the northern part of Massachusetts Bay, so the velocities are smaller. Over Stellwagen Bank the velocities are a bit larger, due to the shoaling over the bank, but not nearly so strong as those in the South Channel. The Tidal ellipses are plotted in Figures 16 and 19 so that the tidal excursion (the actual path taken by a parcel of water moving through the tidal eclipse as measured at the mooring) is 5.1 times larger than reality. The currents off Manomet Point and in Cape Cod Bay are South and North as required to move water into Cape Cod Bay, but smaller in amplitude since there is a wider cross section through which to move the water. At the Boston Buoy the currents are in and out of Boston Harbor, still with remarkably elliptical flow. The currents in Broad Sound show the most circular ellipses, and are aligned more with the bathymetry. The typical tidal current in Massachusetts Bay (away from the mouth and channels) is about 10 cm/sec from top to bottom. The strong structure seen in the currents during other seasons (typified by the third section in Table 7) is due to the internal tides as discussed below.

4. INTERNAL TIDES:

4.1 Internal Tide Generation and Propagation

In regions where there are topographic barriers such as Stellwagen Bank between the Gulf of Maine and Massachusetts Bay, the tide is forced up and over the bank and down into Stellwagen Basin on the flood, and back up and over on the ebb. This creates strong,

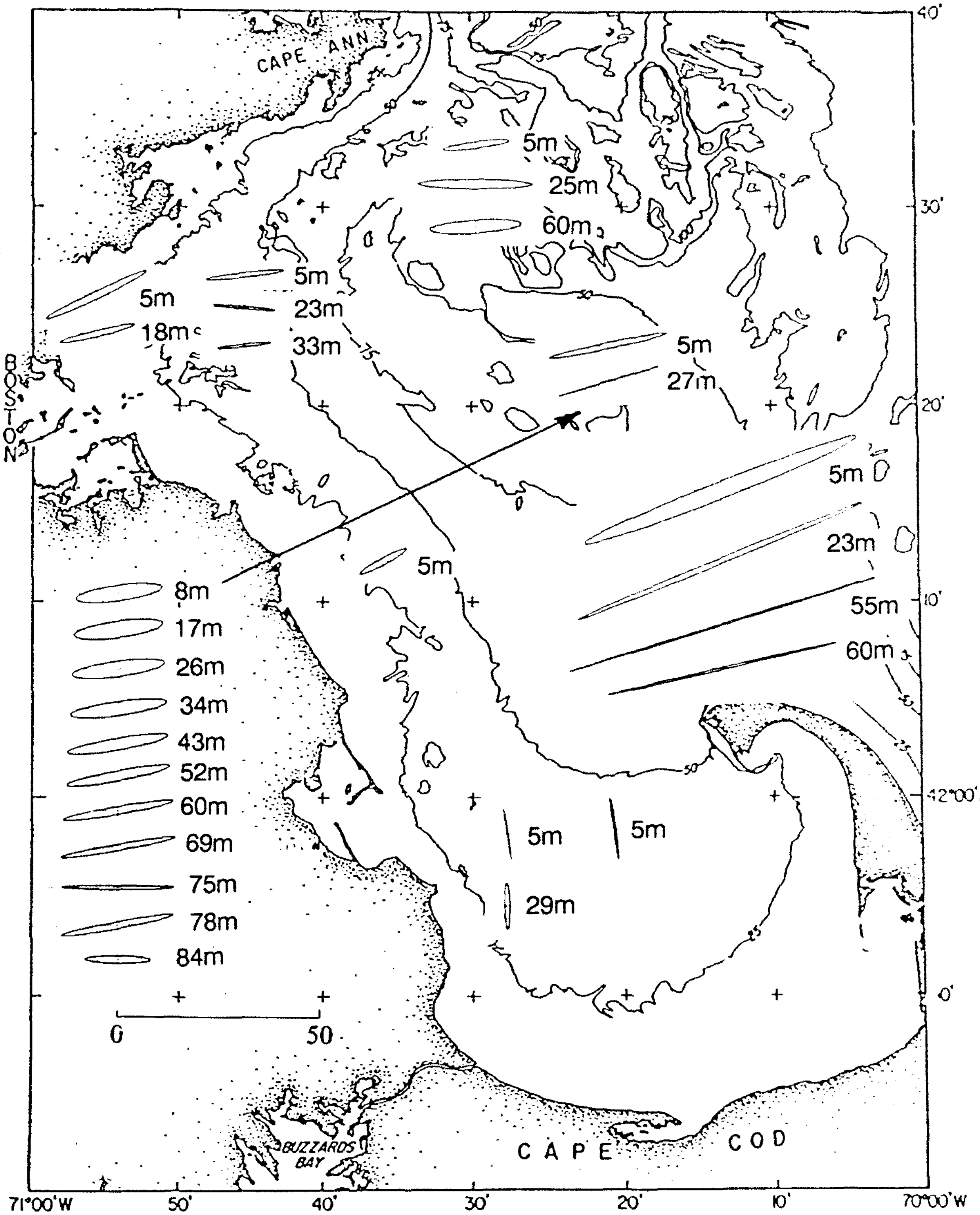


Figure 19. The vertical structure of the current ellipses for the winter observations (Table 6) is shown. The velocity scale is shown in the lower left. The velocity ellipses are shown scaled to 5 times the magnitude of the tidal excursion. The Stellwagen Basin Doppler currents are shown at the left, with the ellipses at 75 and 84 m being USGS VACM and bottom stress tripod current measurements.

periodic currents which distort the density structure of the water column in the region of the bank, and generate internal tides (Rattray et al., 1969, Baines, 1973, Halpern, 1971, Lee and Beardsley, 1974, Haury et al., 1979 and 1983, Chereskin, 1983, and Hibiya, 1988). Internal tides are internal waves at tidal frequency which exist because of the restoring force due to the stratification in the water column. They require the stratification to exist as freely propagating waves and disappear during well-mixed times with no stratification in the winter. In the spring, summer and fall they can become quite large, and have the potential to break and cause mixing in the water column. The generation of internal tides extracts energy from the surface tides to create the internal waves. These waves can then propagate into coastal regions and to the bottom of the deep bays to increase the current velocity which may help to resuspend sediments.

Internal tides can be analyzed by internal wave theory (e.g. Munk and Phillips, 1968, Garrett and Munk, 1971 and 1972) at tidal frequencies. However, these theories generally consider free wave solutions far removed from lateral and vertical boundaries. This is obviously not the case in this region. However, at semidiurnal tidal frequencies with the stratification observed in July 1990, the typical mode one internal wave velocity is about 53 cm/sec and the wavelength is about 24 km. Thus the Stellwagen Basin mooring is well within one wavelength of the generation region on Stellwagen Bank (see Figure 1).

Internal wave energy propagation and particle motion is along "characteristics" defined by the density stratification expressed as the Brunt Väisälä or buoyancy frequency, N, the internal wave frequency, σ, and the inertial frequency, f. This slope is

$$\frac{dx}{dz} = \frac{N^2 - \sigma^2}{\sigma^2 - f^2}$$

As the frequency approaches N the water oscillates up and down at the Brunt Väisälä frequency and the energy is trapped and can not propagate. As the frequency approaches the inertial frequency, the motion becomes horizontal and the energy is again trapped. At frequencies between f and N, the energy propagates along the characteristics whose slope is defined by the above equation. This is also the ratio of the horizontal to vertical wavenumber, and the horizontal to vertical particle motion or horizontal displacement to vertical displacement.

However, in shallow seas, with large amplitude internal waves or when a strong gradient exists making the water column approach a two-layer system, another class of internal waves exist called solitary waves or solitons. These appear as a single wave of depression (or elevations) with ringing at the Brunt Väisälä frequency on the trailing edge (Osborne and Burch, 1980, Haury et al., 1983 . Again the propagation speed of the first mode is about 50 cm/sec, so the distance between solitons is again about 20 km, or about half the distance from Stellwagen Bank to the coast across Massachusetts Bay. The detailed study of the internal tide behavior is inappropriate here, but it is important to mention that the problem of internal tides is complicated, that they exist with large amplitudes in Massachusetts Bay and that they complicate the tidal current analysis attempted here .

The data collected in Massachusetts Bay clearly show a barotropic tide and currents with a strong internal tidal component superimposed during the portion of the year when the water column is stratified. Vertical excursions are often greater than 10 meters in water as shallow as 40 meters in Cape Cod Bay, and as great as 20 meters in the deeper Stellwagen Basin. Figure 20 shows a depth recorder record taken near the mooring in Cape Cod Bay (see Figure 1 for location). The top and bottom are constant, while the strong density gradient regions, marked by high acoustic scattering, are observed to move up and down

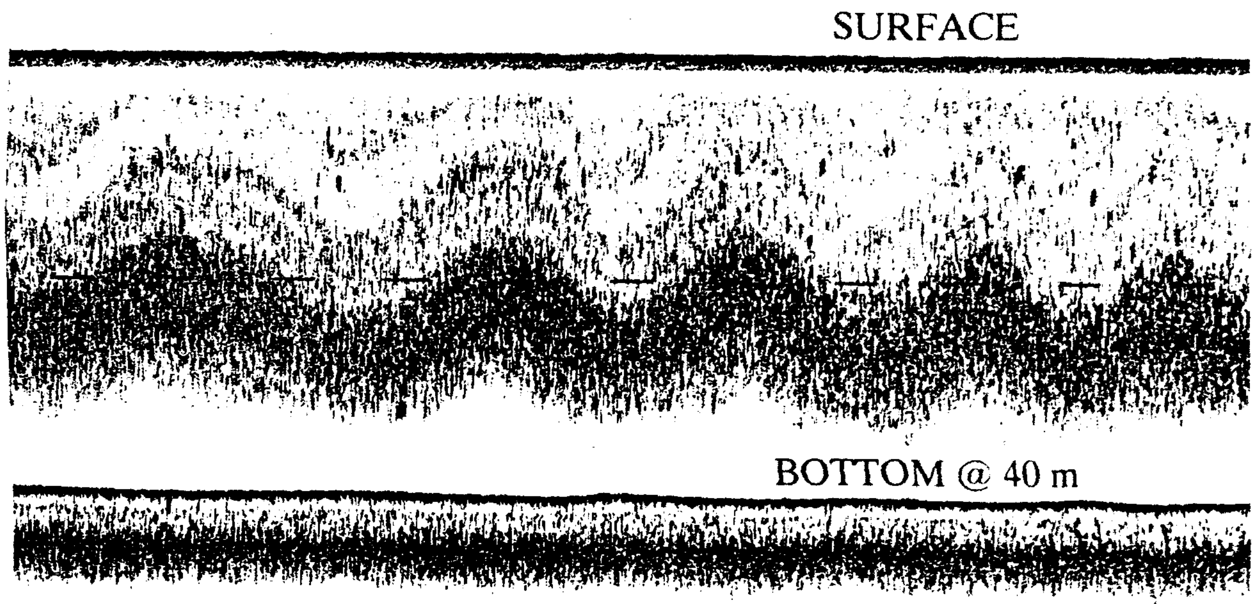


Figure 20. A depth sounder record taken on 24 July 1990 starting at 0910 UTC at the Cape Cod mooring during servicing. The surface and bottom are steady, while the 10 meter vertical excursions of the pycnocline are clearly visible. The period of the oscillations is 7-15 minutes, in agreement with a depth-averaged Brunt Väisälä frequency of 12 minutes.

with 10 meters amplitude and period of about the Brunt Väisälä frequency of 12 minutes. The ship was nearly stationary by the buoy and the internal wave was observed to propagate past the ship. These high frequency internal wave oscillations were not resolved by the moored instrumentation which recorded hourly averages.

During the July servicing when the water was calm, bands of internal wave slicks were observed on the radar where convergence zones had fewer surface ripples, and scattered the radar signal less. This was also seen by Trask and Briscoe (1983) in this region in 1977. They also presented synthetic aperture radar images from SEASAT showing the spatial distribution of the surface effects of the internal waves in Massachusetts Bay. Internal wave packets propagating shoreward from Stellwagen Bank could be clearly seen.

4.2. Internal Tides over Stellwagen Bank

The winter tidal velocities are typically less than 20 cm per second (with the exception of nearly 1 knot tidal currents in the channel north of Race Point) and aligned as one would expect for moving the water in and out of Massachusetts Bay to produce the observed tidal elevation change. Figure 21 shows the tide elevation and current on Stellwagen Bank from mid-November through mid-December. The current is very regular with an equal inflow and outflow. The strongest tidal currents were seen over Stellwagen Bank during the summer when the twice a day velocities (in the generation region of the internal tides) regularly exceed 1 knot (see Figure 22). The tidal elevation is still the same. and the maximum current flow out of Massachusetts Bay is about the same, but the current into Massachusetts Bay is now over twice as large. This additional energy is due to the internal tides. Tidal velocities during the winter (from November into March) are typically only half those seen the rest of the year due to the absence of internal tides when the Bays are well mixed. In Stellwagen Basin, there is a small intensification of tidal velocities with depth. By distorting the density field, the internal tides make it difficult to interpret the bay-wide hydrographic surveys, and mask the lower frequency wind and density driven circulation signals in moored observations. Internal waves exist everywhere and must be considered as a significant source of energy along with the waves, wind and density driven currents when considering the resuspension and transport of sediments in the Massachusetts Bays system.

The current record from the bottom on Stellwagen Bank (Figure 4) shows a marked change in amplitude of the velocity during late September and October 1990. This is the time when the temperature and salinity in Stellwagen Basin became well mixed vertically and could no longer support internal oscillations. This is shown by the moored density observations made at the Stellwagen Basin mooring (see Figure 16 for configuration) and plotted in Figure 23. The amplitude of the velocity is clearly less than one half during the winter. This is again seen in the Stellwagen Basin Doppler profiler records which were analyzed by the harmonic method for the spring 1991 period (Table 7 and Figure 23). At the M2 frequency, the velocity record is now obviously depth dependent . The current ellipses are now observed to turn clockwise with depth, and the ellipticity and magnitude show greater change. The amplitude and phases (bottom of Figure 24) also show this baroclinic behavior in the flow.

4.2. Separation of Barotropic and Baroclinic Currents

To attempt to separate the internal wave component from that part of the current due to the surface elevation, the winter tidal analysis was used to predict the tidal velocities for the spring period, and to subtract the predicted barotropic tide from the observed to

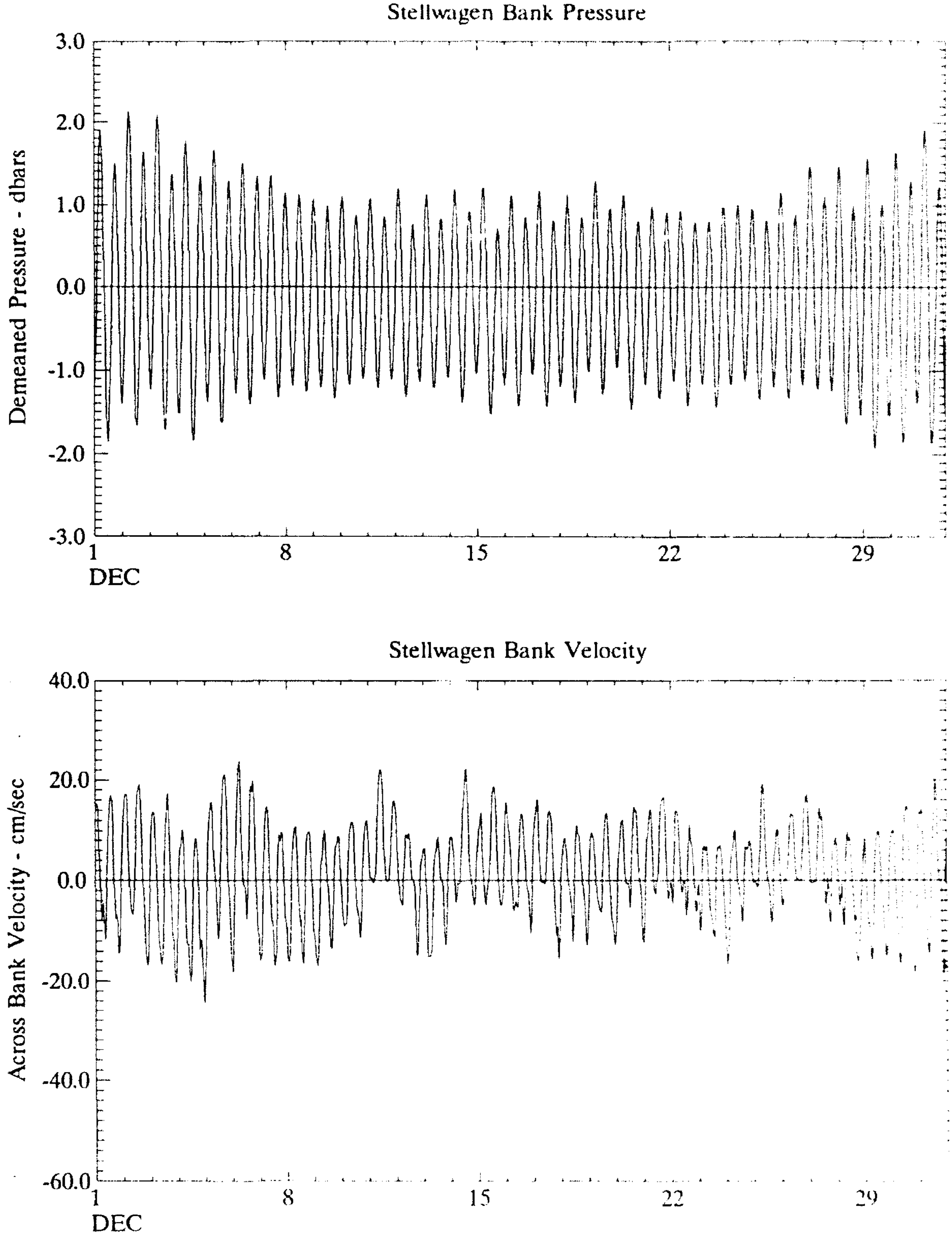
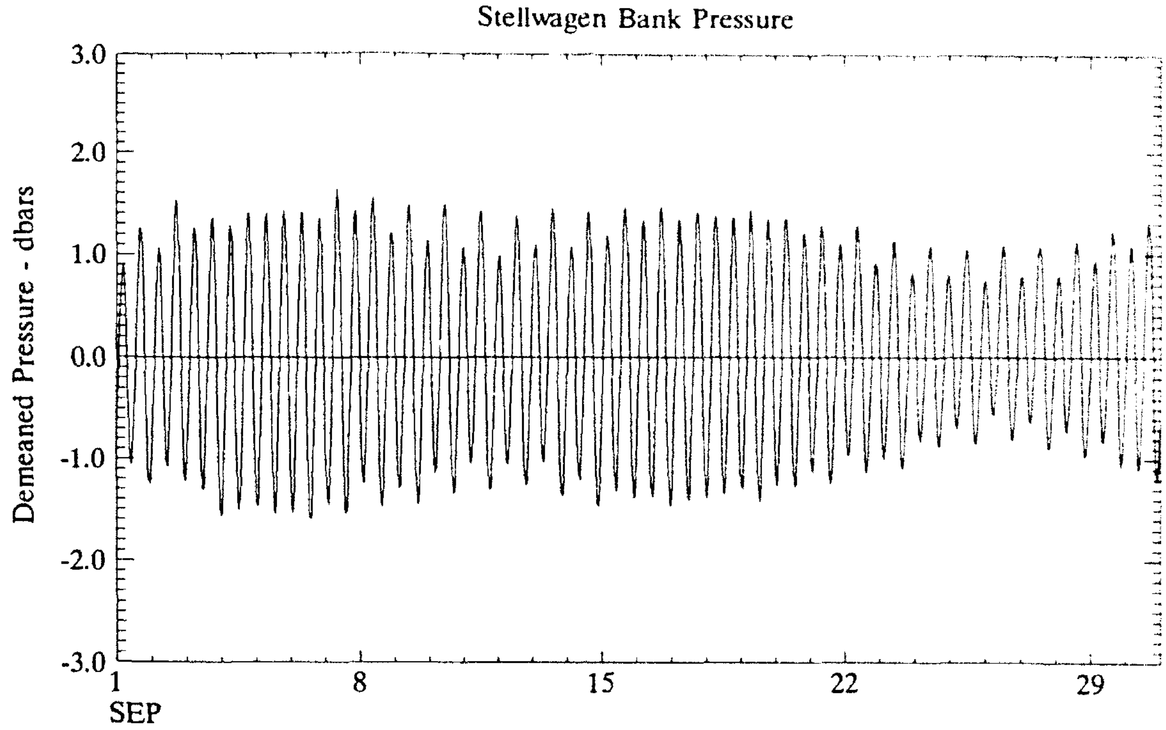


Figure 21. The pressure observation (top) and across bank velocities (bottom) for December 1990. The velocities show equal flow into and out of Massachusetts Bay.



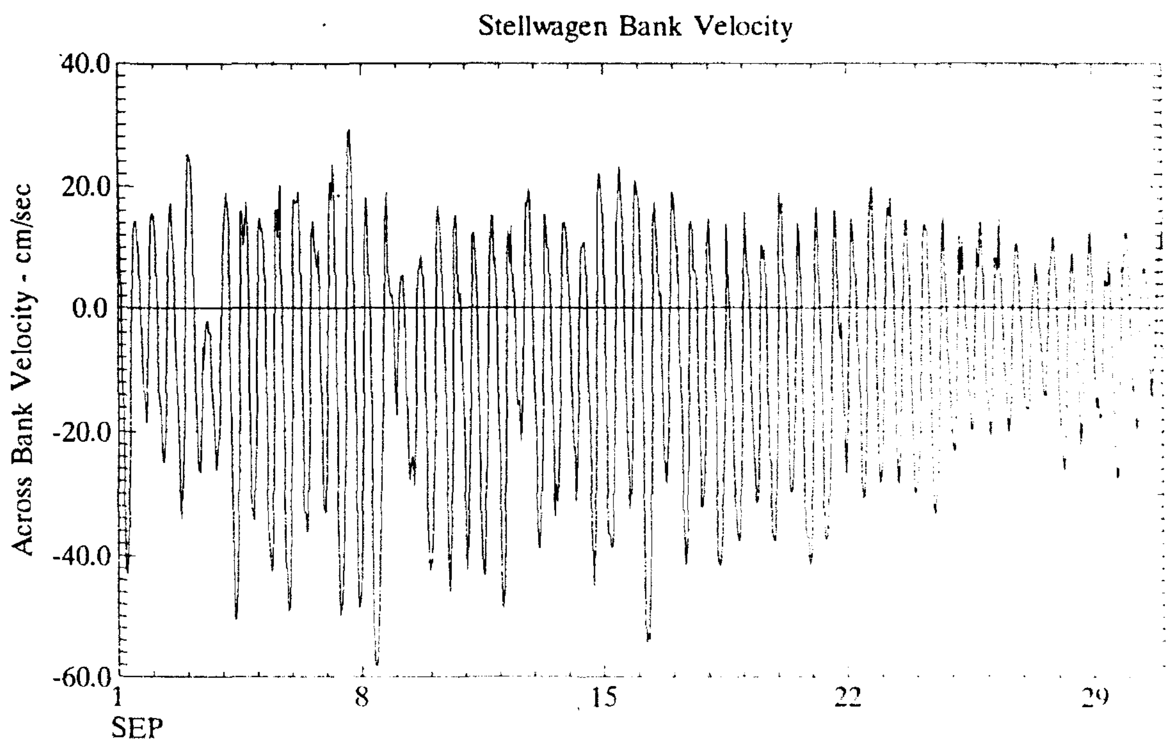


Figure 22. The pressure observation (top) and across bank current component (bottom) for the month of September are plotted on the same scale as Figure 21. The velocities flowing into Massachusetts Bay are now more than twice as large as during the winter.

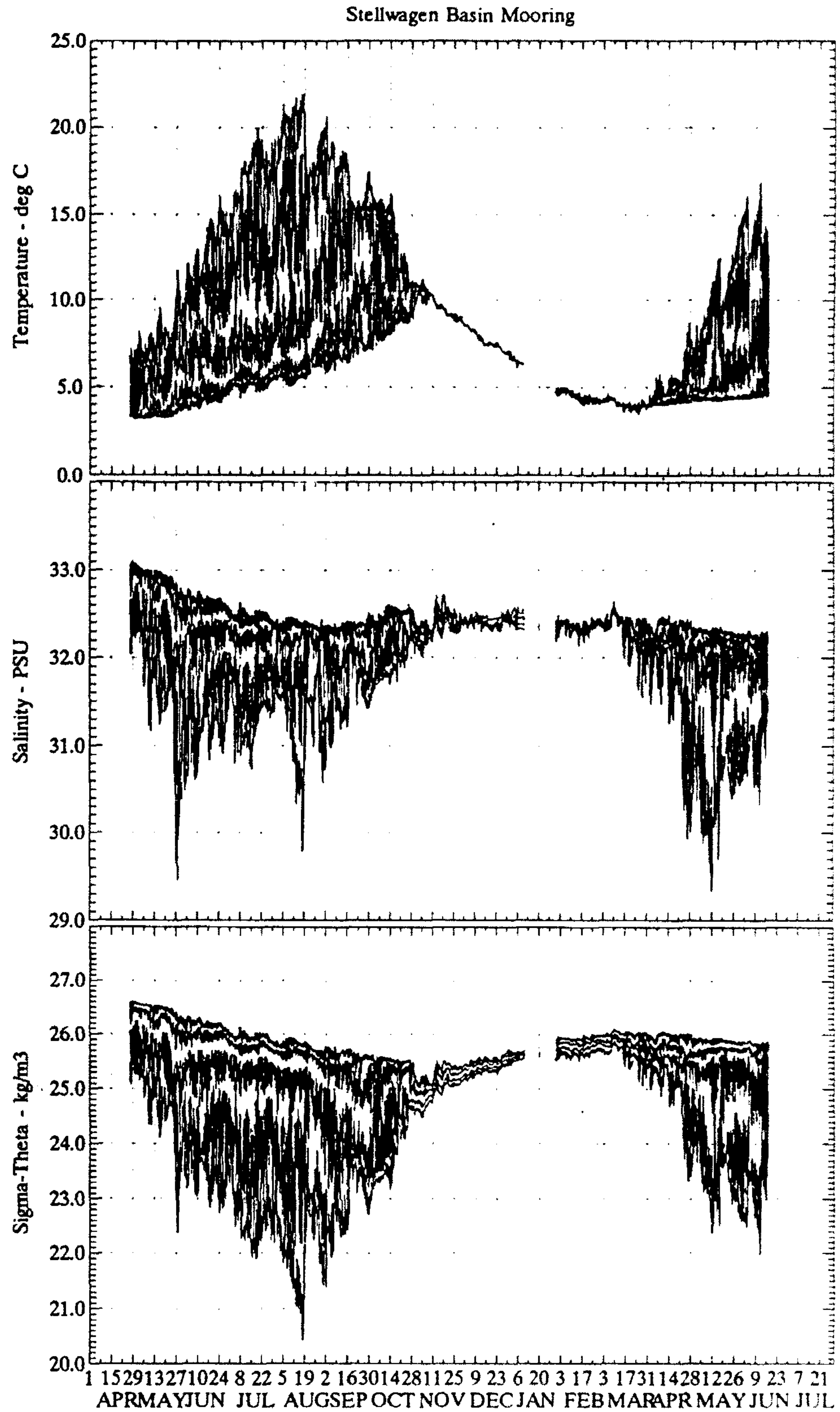


Figure 23. Time series of temperature (top), salinity (middle) and density (bottom) from Stellwagen Basin illustrating the spring/summer stratification and winter well-mixed water column.

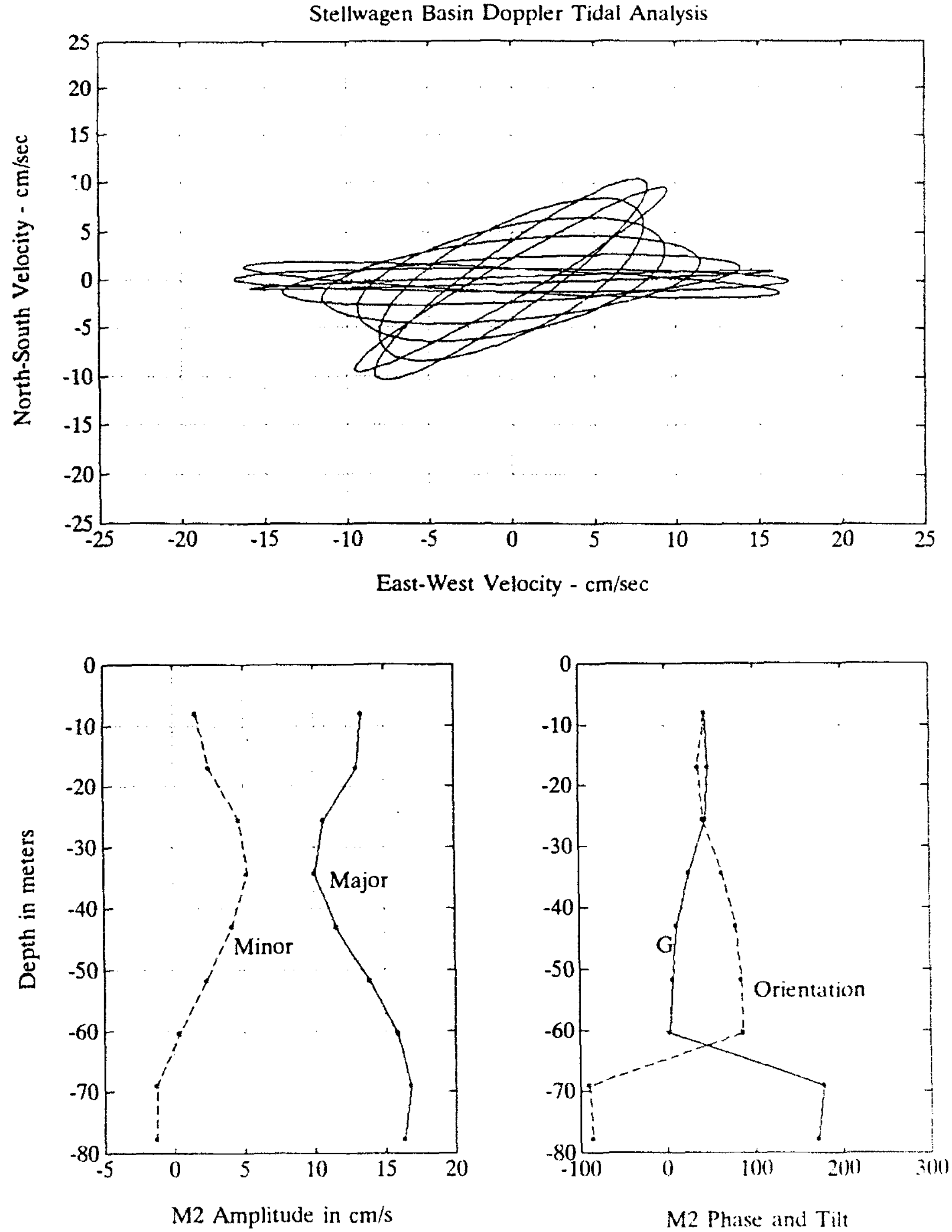


Figure 24. The Spring 1991 (15 March to 18 June 1991) Stellwagen Basin Doppler profile at the M2 frequency. The tidal ellipses (top panel) now turn clockwise from the surface to the bottom. The ellipses get rounder at mid depths and become more elliptical at the bottom. The rotation of ellipse tilt is about 50 degrees (see Table 7). The amplitude and phase at the bottom indicate the baroclinic (internal wave) nature of the flow. The major axis is in solid and the minor axis dashed lower left (negative implies clockwise rotation of the velocity vector), and the Greenwich phase is solid and ellipse tilt is dashed lower right.

leave the baroclinic tide and background velocity fluctuations. This baroclinic and background current record was then analyzed for the M2 component of the tide, to separate out the background signal. The results are listed at the bottom of Table 7 plotted in Figure 25. The amplitudes (lower panel) show a maximum velocity at the surface and bottom, and a minimum at about 40 meters, just below the pycnocline. The phases show a 180 degree phase reversal at this depth. The ellipses (top of Figure 25) now are nearly circular, and are largest at the surface and bottom with a minimum amplitude at mid-depth. This is clearly a first mode internal oscillation with the surface and bottom currents 180 degrees out of phase, and the maximum horizontal velocities occurring at the top and bottom and the greatest vertical amplitudes seen at mid-depth!

The internal tidal analysis at the bottom of Table 7 is only at the M2 frequency, while the semi-diurnal internal tide band is wider. The analyzed amplitude is about half that of the barotropic currents, but from the time series and spectra, it is obvious that the semi-diurnal internal tide (over the entire band) is about the same size as the barotropic current.

With this caution of the potential contamination of a tidal analysis due to internal tidal effects, and the accompanying error in using these "contaminated" results for prediction or model comparisons, the tides from all four seasons were analyzed by the least squares technique and the results given in Table 8 for the O1 constituent, Table 9 for the K1 constituent, Table 10 for the N2 constituent, Table 11 for the M2 constituent, Table 12 for the S2 constituent, Table 13 for the M4 compound tidal constituent and Table 14 for the M6 compound constituent. The four seasons were defined as: (1) winter from 1 November to 1 March, (2) spring from 1 March to 1 June, (3) summer from 1 June to 1 September. and Fall from 1 September to 1 November. The divisions were roughly based on partitioning the year into four pieces during which similar processes and statistics were occurring.

5. SUMMARY:

Observations of bottom pressure and currents were made at selected sites in Massachusetts and Cape Cod Bays from spring 1990 through spring 1991. Since the tides dominated the sea surface elevation and current spectra, extra effort was spent in understanding the tides in this region. Representative pressure and current records were analyzed for their tidal constituents by the harmonic, response and least squares methods. The results agreed well except at the S2 frequency where the response method indicated radiational (i.e. sea breeze) effects may complicate the analysis. The M2 tidal constituent dominated the variance. For sea surface elevation, 92% of the variance in the entire record was at the M2 frequency, indicating that using this constituent alone gives a good description of the tides. In the diurnal and semidiurnal bands, the amplitude and phase of each tidal constituent indicated that the sea surface was rising and falling the same amount and in phase. There is a hint of amplification in Provincetown and Boston harbors. Being part of the Gulf of Maine/Bay of Fundy system, which is in resonance just below the semidiurnal band, the N2 and M2 constituents are amplified over the S2, so the modulation of the amplitude by the beating of these lines is predominantly monthly rather than fortnightly. A representative current record was also analyzed by the three methods, which again agreed. However, the analysis and interpretation of the current observations are complicated by the presence of interval waves which are generated over Stellwagen Bank and propagate across Massachusetts and Cape Cod Bays. These internal oscillations exist on the density gradient in the spring, summer and fall, and nearly disappear during the winter when the water column is well mixed. The internal tidal contamination needs to be eliminated from the analysis in order that the tidal currents can be predicted and compared with model results. To minimize the internal wave effects, current analyses were done during the winter when the water column was well mixed, and with records spanning the longest possible length.

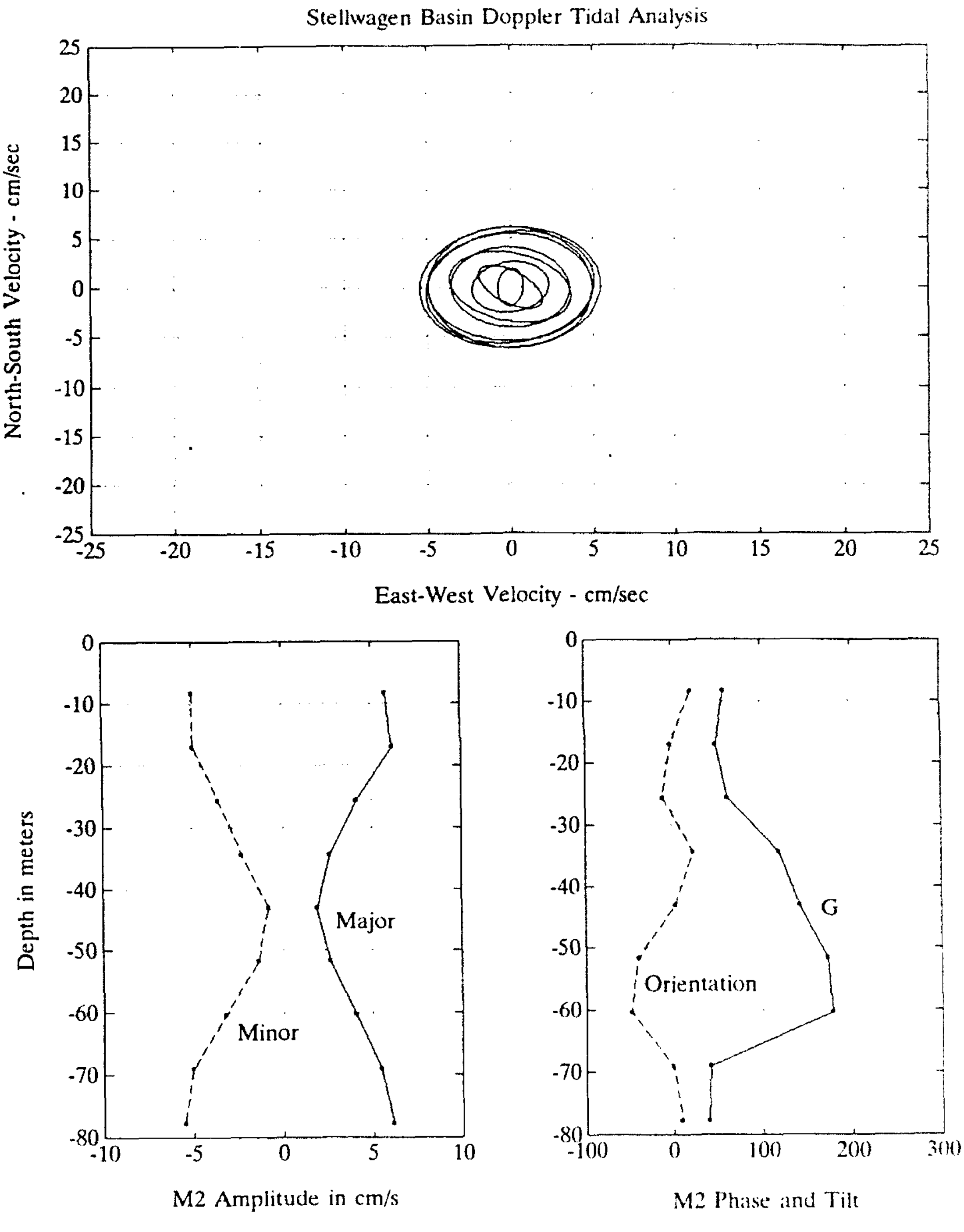


Figure 25. The Spring 1991 internal wave component at the M2 frequency at the Stellwagen Basin Doppler mooring was constructed by subtracting a predicted tide based on the winter analysis (Figure 18) from the observed spring tides (Figure 24). The ellipses in the top panel show a nearly circular current with maximum amplitudes at the surface and bottom and a minimum at about 40 meters depth. This is shown at the bottom and the phase is observed to change by about 180 degrees, indicating that the top currents are out of phase with the bottom, or nearly a classic first mode internal wave velocity structure. The major axis is in solid and the minor axis dashed lower left (negative implies clockwise rotation of the velocity vector), and the Greenwich phase is solid and ellipse tilt is dashed lower right.

The results were not so simple as the surface elevations. The tidal currents were generally less than 20 cm/sec in the Bays, except in the deep channel between Race Point and Stellwagen Bank where tidal currents approached 1 knot. Currents were aligned with the flow required to transport the water in and out of the Massachusetts and Cape Cod Bays to produce the nearly simultaneous rise and fall of the sea surface observed at all the stations.

During the winter, the vertical structure of the currents was generally fairly uniform with depth, with small and systematic changes in major and minor axis amplitudes and ellipse orientation which were probably due to bathymetric effects. A detailed analysis of the current structure was carried out on the observations made by an acoustic Doppler current profiler in Stellwagen Basin. The winter record showed an ellipse oriented perpendicular to Stellwagen Bank which was nearly uniform in amplitude with depth. In the spring when the water column was well stratified, the profile showed large changes in amplitude and phase. Subtracting a predicted tide based on the analysis of the winter record resulted in a profile which fit a mode one internal wave. The barotropic or predicted part of the tidal currents is only about 1/4 of the record variance in the semidiurnal band. The rest of the energy is internal or baroclinic and important for mixing and resuspending sediments in the deep bays.

6. ACKNOWLEDGEMENTS:

The field component of this work was supported by the Massachusetts Bays Program, administered through the Massachusetts Coastal Zone Management Office and the United States Geological Survey, Woods Hole Branch. This analysis work was supported by the U.S. Geological Survey, Woods Hole Branch.

TABLE 8 - Least Squares Analysis for the O1 Tidal Currents

Series		Major	Minor	Tilt	Phase
Broad Sound	- Winter 1990	0.90	0.08	41.0	345.6
@ 5 m	- Spring 1991	0.62	-0.10	68.7	292.8
Broad Sound	- Spring 1990	0.35	-0.02	27.3	295.6
@ 18 m	- Summer 1990	0.32	-0.03	15.9	288.7
	- Fall 1990	0.56	0.15	-2.1	280.5
	- Winter 1990	0.39	-0.12	65.4	253.4
Boston Bucy	- Winter 1989	0.70	-0.25	89.6	271.9
@ 5 m	- Spring 1990	0.70	-0.09	80.6	297.4
	- Summer 1990	0.93	-0.17	81.5	267.4
	- Winter 1990	0.44	-0.14	-88.8	121.2
	- Spring 1991	0.91	-0.36	19.8	287.2
	- Summer 1991	1.11	0.02	-59.2	89.6
Boston Buoy	- Winter 1989	0.49	-0.05	76.7	313.7
@ 23 m	- Spring 1990	0.46	-0.03	-80.5	61.0
	- Summer 1990	0.40	-0.03	-87.0	114.5
	- Fall 1990	0.84	0.00	86.0	255.2
	- Spring 1991	0.53	0.18	-56.1	48.4
	- Summer 1991	0.49	-0.23	73.1	249.6
Boston Buoy	- Spring 1990	0.70	0.09	-83.3	40.3
@ 33 m	- Summer 1990	0.25	-0.06	67.5	315.3
	- Winter 1990	0.29	-0.07	87.6	278.3
	- Spring 1991	0.39	0.04	-65.7	12.0
	- Summer 1991	0.13	-0.07	7.1	237.5
Manomet Point	- Fall 1990	0.48	0.26	49.0	274.4
@ 5 m	- Winter 1990	0.58	-0.14	-8.1	307.1
	- Spring 1991	0.71	0.00	-3.3	300.3
Manomet Point	- Fall 1990	0.45	0.36	84.0	203.3
@ 29 m	- Winter 1990	0.53	0.14	9.2	270.4
	- Spring 1991	0.54	0.02	10.5	287.6
Race Point	- Fall 1990	1.44	0.61	-16.2	330.5
@ 5 m	- Winter 1990	1.93	0.37	43.6	278.1
	- Spring 1991	2.24	0.01	55.7	239.0
Race Point	- Fall 1990	2.61	0.00	77.6	239.1
@ 23 m	- Winter 1990	1.26	-0.15	62.4	271.1
Race Point	- Fall 1990	2.06	-0.30	42.4	262.3
@ 55 m	- Winter 1990	1.30	0.18	61.9	252.6
	- Spring 1991	1.04	0.29	78.1	242.1
Race Point	- Winter 1990	1.49	0.28	-85.8	59.3
@ 60 m	- Spring 1991	0.78	0.21	86.5	239.8
Scituate	- Summer 1990	1.16	-0.43	-82.1	96.0
@ 5 m	- Fall 1990	0.81	0.49	-42.2	69.9
	- Winter 1990	0.30	0.04	81.9	294.0
	- Spring 1991	0.70	0.12	-23.7	312.9
Scituate	- Spring 1990	0.39	0.06	-79.2	68.4
@ 23 m	- Summer 1990	0.30	0.14	-34.1	325.5
	- Spring 1991	0.75	0.04	89.4	254.2
Stellwagen Basin	- Fall 1990	1.37	0.22	-79.3	18.1
@ 75 m	- Winter 1990	0.82	0.18	-74.7	58.3
	- Spring 1991	0.96	0.29	-69.6	37.4

Stellwagen Basin	- Fall 1990	0.97	0.21	-87.6	20.2
@ 84 m	- Winter 1990	0.49	0.24	85.1	241.1
	- Spring 1991	0.89	0.04	-70.7	20.2
North Channel	- Summer 1990	2.26	-0.99	-42.8	65.0
@ 4 m	- Fall 1990	1.51	-0.48	3.3	54.5
	- Winter 1990	0.76	0.50	29.0	346.0
North Channel	- Spring 1990	0.92	0.05	-69.4	53.9
@ 25 m	- Summer 1990	0.47	0.00	71.0	336.2
	- Winter 1990	1.15	0.25	67.0	27.9
	- Spring 1991	0.57	0.05	56.4	293.1
North Channel	- Summer 1990	0.75	0.01	67.5	344.6
@ 60 m	- Fall 1990	0.62	0.22	51.4	358.8
	- Winter 1990	1.21	0.36	33.2	353.7
	- Spring 1991	0.94	0.32	36.7	7.7
Stellwagen Bank-	Summer 1990	1.65	-0.93	-89.6	140.9
@ 4 m	- Fall 1990	1.18	0.43	83.7	333.1
	- Winter 1990	0.73	-0.09	60.4	309.9
	- Spring 1991	1.37	-0.07	1.5	352.0
Stellwagen Bank-	Summer 1990	1.21	0.07	25.0	154.6
@ 25 m	- Fall 1990	0.89	0.17	47.7	111.5
	- Winter 1990	0.55	0.04	27.3	139.5
	- Spring 1991	0.82	-0.10	22.3	152.8
Stellwagen Basin	- Spr 1990	1.34	0.38	32.7	207.4
@ 8 m	- Summer 1990	0.73	0.00	52.5	166.6
	- Fall 1990	0.75	-0.01	58.4	281.9
	- Winter 1990	0.23	0.06	-34.5	7.8
	- Spring 1991	1.21	0.17	15.9	333.5
Stellwagen Basin	- Spr 1990	1.35	-0.48	12.6	169.5
@ 28 m	- Summer 1990	0.72	-0.20	42.6	199.7
	- Fall 1990	0.51	-0.18	75.5	322.3
	- Winter 1990	0.60	0.12	-68.6	98.4
	- Spring 1991	0.92	0.09	-1.8	345.8
Stellwagen Basin	- Spr 1990	1.36	0.40	-77.5	278.9
@ 72 m	- Summer 1990	0.61	0.31	-89.1	277.1
	- Fall 1990	0.98	0.10	87.2	242.2
	- Winter 1990	1.03	0.15	87.0	282.1
	- Spring 1991	1.13	0.35	-75.5	57.0
Cape Cod Bay	- Spring 1990	1.03	-0.27	-22.9	346.6
@ 4 m	- Summer 1990	0.59	-0.17	-55.6	353.5
	- Fall 1990	1.37	-0.01	-46.9	332.3
	- Winter 1990	0.63	-0.15	20.4	299.4
Cape Cod Bay	- Spring 1990	0.52	-0.06	7.8	250.1
@ 25 m	- Spring 1991	0.47	0.27	5.6	303.9

TABLE 9 - Least Squares Analysis for the K1 Tidal Currents

Series		Major	Minor	Tilt	Phase
Broad Sound	- Winter 1990	1.29	-0.39	29.5	313.8
@ 5 m	- Spring 1991	0.78	0.28	-243.9	85.1
Broad Sound	- Spring 1990	1.22	0.15	-265.3	298.9
@ 18 m	- Summer 1990	0.37	0.28	-240.5	296.9
	- Fall 1990	0.75	0.30	-201.2	49.6
	- Winter 1990	0.47	-0.12	38.1	282.7
Boston Buoy	- Winter 1989	0.47	0.03	-189.5	102.7
@ 5 m	- Spring 1990	1.64	-0.70	-208.1	26.6
	- Summer 1990	1.27	-0.79	-240.7	89.3
	- Winter 1990	0.50	-0.11	11.4	295.3
	- Spring 1991	2.49	-1.62	80.5	110.2
	- Summer 1991	2.04	-1.11	-224.0	91.4
Boston Buoy	- Winter 1989	0.56	0.01	14.0	281.4
@ 23 m	- Spring 1990	1.26	-0.62	4.7	318.3
	- Summer 1990	0.53	-0.13	58.7	316.0
	- Fall 1990	1.17	-0.24	-267.6	34.4
	- Spring 1991	1.29	-0.74	21.1	326.5
	- Summer 1991	0.60	-0.17	51.3	305.9
Boston Buoy	- Spring 1990	1.05	-0.49	-191.9	160.0
@ 33 m	- Summer 1990	0.24	0.02	-261.2	316.8
	- Winter 1990	0.35	0.04	38.9	281.5
	- Spring 1991	0.62	-0.32	-206.5	224.7
	- Summer 1991	0.17	-0.02	-255.3	297.3
Manomet Point	- Fall 1990	2.63	-0.64	47.9	293.1
@ 5 m	- Winter 1990	0.69	-0.03	84.5	291.3
	- Spring 1991	1.89	-1.65	22.8	141.4
Manomet Point	- Fall 1990	0.81	-0.53	-214.0	357.3
@ 29 m	- Winter 1990	0.58	-0.01	-261.3	303.3
	- Spring 1991	1.69	-0.24	65.2	305.0
Race Point	- Fall 1990	5.84	-1.76	26.0	300.0
@ 5 m	- Winter 1990	2.42	-0.23	38.3	285.7
	- Spring 1991	2.09	1.65	-262.8	26.4
Race Point	- Fall 1990	1.27	0.02	-197.9	46.1
@ 23 m	- Winter 1990	1.86	0.07	39.7	275.5
Race Point	- Fall 1990	3.69	0.45	35.9	257.4
@ 55 m	- Winter 1990	1.81	0.27	29.0	274.3
	- Spring 1991	2.56	-0.60	22.8	303.5
Race Point	- Winter 1990	1.09	0.00	-182.7	93.5
@ 60 m	- Spring 1991	1.78	-0.32	7.6	304.3
Scituate	- Summer 1990	1.02	-0.17	-183.6	78.8
@ 5 m	- Fall 1990	2.18	-0.42	44.4	299.4
	- Winter 1990	0.44	-0.10	82.5	297.1
	- Spring 1991	2.12	-1.66	82.4	122.3
Scituate	- Spring 1990	0.94	-0.16	51.2	329.8
@ 23 m	- Summer 1990	0.39	-0.23	31.8	344.3
	- Spring 1991	0.92	-0.61	10.4	19.2
Stellwagen Basin	- Fall 1990	1.41	0.38	-204.0	57.8
@ 75 m	- Winter 1990	0.81	0.46	1.0	270.0
	- Spring 1991	0.82	0.28	5.2	283.9

Stellwagen Basin @ 84 m	- Fall 1990	1.10	0.28	-191.7	76.2
	- Winter 1990	0.47	0.43	29.2	283.4
	- Spring 1991	0.59	0.41	-190.1	111.2
North Channel @ 4 m	- Summer 1990	4.25	-1.97	-199.4	108.7
	- Fall 1990	5.00	-3.01	27.6	318.4
	- Winter 1990	0.79	-0.57	40.8	331.6
North Channel @ 25 m	- Spring 1990	2.27	-0.91	41.7	352.8
	- Summer 1990	0.82	-0.20	48.9	336.2
	- Winter 1990	0.54	-0.28	-261.8	23.8
	- Spring 1991	1.93	-0.70	47.4	3.1
North Channel @ 60 m	- Summer 1990	0.50	0.06	41.6	9.2
	- Fall 1990	1.14	0.08	88.3	67.9
	- Winter 1990	0.52	0.25	-255.5	67.5
	- Spring 1991	1.94	-1.13	-187.3	158.5
Stellwagen Bank- @ 4 m	Summer 1990	4.40	-3.12	-202.0	102.0
	- Fall 1990	4.46	-3.00	19.0	311.0
	- Winter 1990	0.90	-0.06	55.2	313.3
	- Spring 1991	4.82	-2.43	-266.8	89.1
Stellwagen Bank- @ 25 m	Summer 1990	1.45	-0.08	66.8	167.1
	- Fall 1990	1.98	-0.39	83.6	210.0
	- Winter 1990	0.81	-0.05	72.7	133.3
	- Spring 1991	1.75	-0.27	26.8	131.7
Stellwagen Basin @ 8 m	- Spr 1990	1.70	-0.38	-193.5	291.0
	- Summer 1990	1.07	-0.10	61.2	165.5
	- Fall 1990	1.24	-0.20	68.5	326.7
	- Winter 1990	0.69	-0.06	56.1	314.1
	- Spring 1991	1.11	0.47	-249.7	18.2
Stellwagen Basin @ 28 m	- Spr 1990	2.52	-1.78	38.7	173.9
	- Summer 1990	1.10	-0.37	62.9	172.0
	- Fall 1990	1.80	-0.57	-266.3	354.6
	- Winter 1990	0.75	0.05	46.9	297.4
	- Spring 1991	1.40	0.00	40.4	323.1
Stellwagen Basin @ 72 m	- Spr 1990	1.80	-0.05	3.1	127.9
	- Summer 1990	0.87	0.41	12.8	117.9
	- Fall 1990	0.87	0.27	-202.8	67.7
	- Winter 1990	0.65	0.51	48.5	310.1
	- Spring 1991	1.53	0.39	-180.3	96.3
Cape Cod Bay @ 4 m	- Spring 1990	1.98	-0.89	24.0	153.2
	- Summer 1990	2.05	-0.82	0.2	198.3
	- Fall 1990	2.75	-0.55	55.4	279.4
	- Winter 1990	0.94	-0.05	83.9	281.4
Cape Cod Bay @ 25 m	- Spring 1990	1.84	-1.03	70.9	285.8
	- Spring 1991	1.80	-1.03	83.2	289.1

TABLE 10 - Least Squares Analysis for the N2 Tidal Currents

Series		Major	Minor	Tilt	Phase
Broad Sound	- Winter 1990	4.39	0.28	46.1	181.4
@ 5 m	- Spring 1991	3.81	-0.38	51.9	201.2
Broad Sound	- Spring 1990	2.44	0.51	82.5	117.2
@ 18 m	- Summer 1990	2.53	0.58	-70.2	280.0
	- Fall 1990	1.69	0.64	68.4	136.0
	- Winter 1990	2.89	0.48	67.9	151.1
Boston Buoy	- Winter 1989	1.88	0.05	78.1	143.6
@ 5 m	- Spring 1990	1.62	-0.60	84.6	156.1
	- Summer 1990	2.45	-0.63	-56.8	281.9
	- Winter 1990	2.63	-0.16	77.0	168.4
	- Spring 1991	2.73	-0.38	84.7	179.7
	- Summer 1991	1.76	0.43	-46.2	291.2
Boston Buoy	- Winter 1989	1.83	0.02	89.2	152.1
@ 23 m	- Spring 1990	2.33	-0.35	83.2	173.4
	- Summer 1990	2.48	-0.36	81.3	171.1
	- Fall 1990	3.29	-1.38	84.1	168.2
	- Spring 1991	1.62	0.17	83.5	171.2
	- Summer 1991	3.08	-0.04	87.6	160.9
Boston Buoy	- Spring 1990	1.68	0.19	-80.7	334.5
@ 33 m	- Summer 1990	1.54	0.07	-71.3	332.3
	- Winter 1990	1.80	0.20	76.4	151.9
	- Spring 1991	1.09	0.12	69.7	149.0
	- Summer 1991	2.48	-0.11	-82.5	327.3
Manomet Point	- Fall 1990	2.75	-0.34	1.9	188.2
@ 5 m	- Winter 1990	2.89	0.13	-3.1	174.7
	- Spring 1991	2.82	-0.47	-8.0	197.6
Manomet Point	- Fall 1990	1.94	0.19	-3.8	194.6
@ 29 m	- Winter 1990	3.09	0.07	-1.0	167.7
	- Spring 1991	2.60	0.19	4.0	176.5
Race Point	- Fall 1990	9.36	0.44	55.3	182.1
@ 5 m	- Winter 1990	10.55	0.17	58.9	164.8
	- Spring 1991	7.35	-0.17	58.8	171.9
Race Point	- Fall 1990	9.67	-3.04	54.7	177.6
@ 23 m	- Winter 1990	10.30	-0.39	55.1	172.1
Race Point	- Fall 1990	6.83	1.44	65.5	157.1
@ 55 m	- Winter 1990	9.34	-0.45	60.2	155.3
	- Spring 1991	6.92	0.98	56.5	155.3
Race Point	- Winter 1990	6.17	0.74	63.5	135.5
@ 60 m	- Spring 1991	4.84	0.41	65.8	155.5
Scituate	- Summer 1990	3.27	-0.21	59.3	158.8
@ 5 m	- Fall 1990	2.02	-0.47	55.4	167.5
	- Winter 1990	1.82	0.36	46.3	167.4
	- Spring 1991	2.31	-0.01	49.2	169.2
Scituate	- Spring 1990	1.24	-0.17	54.8	147.3
@ 23 m	- Summer 1990	1.43	0.56	-84.7	213.8
	- Spring 1991	1.08	0.32	-56.9	201.6
Stellwagen Basin	- Fall 1990	4.79	-0.09	-54.9	301.5
@ 75 m	- Winter 1990	2.98	-0.07	78.7	161.2
	- Spring 1991	2.54	-0.47	-62.2	315.1

Stellwagen Basin	- Fall 1990	2.95	0.29	-53.5	292.9
@ 84 m	- Winter 1990	1.77	0.30	87.6	147.5
	- Spring 1991	1.89	-0.40	-44.1	313.2
North Channel	- Summer 1990	2.81	0.14	-86.1	19.8
@ 4 m	- Fall 1990	2.72	-1.31	83.2	235.9
	- Winter 1990	2.31	0.35	76.9	212.0
North Channel	- Spring 1990	2.69	0.31	-78.3	1.0
@ 25 m	- Summer 1990	1.81	0.61	-58.8	351.8
	- Winter 1990	3.41	1.21	69.7	217.5
	- Spring 1991	2.27	0.35	84.1	207.7
North Channel	- Summer 1990	2.93	-0.75	84.0	223.7
@ 60 m	- Fall 1990	2.06	1.11	-40.4	347.5
	- Winter 1990	2.12	0.79	85.2	203.7
	- Spring 1991	2.54	1.40	-71.7	31.9
Stellwagen Bank	- Summer 1990	6.14	-4.01	86.3	206.7
@ 4 m	- Fall 1990	4.80	-1.05	79.2	216.2
	- Winter 1990	3.18	-0.17	60.0	226.0
	- Spring 1991	6.16	-0.92	66.7	218.6
Stellwagen Bank	- Summer 1990	3.32	0.29	51.7	10.3
@ 25 m	- Fall 1990	4.05	0.12	60.4	17.5
	- Winter 1990	3.40	-0.26	60.4	10.8
	- Spring 1991	2.01	0.42	77.0	1.9
Stellwagen Basin	- Spr 1990	3.75	0.04	42.5	309.6
@ 8 m	- Summer 1990	2.67	0.18	29.9	318.1
	- Fall 1990	0.62	-0.22	18.4	198.6
	- Winter 1990	3.02	0.35	72.1	183.3
	- Spring 1991	2.88	-0.14	45.2	241.6
Stellwagen Basin	- Spr 1990	3.65	0.47	62.6	298.5
@ 28 m	- Summer 1990	2.18	1.24	49.0	303.7
	- Fall 1990	1.78	-0.56	14.8	159.6
	- Winter 1990	3.15	0.63	69.9	196.0
	- Spring 1991	2.09	0.48	31.5	248.2
Stellwagen Basin	- Spr 1990	4.36	-0.05	-85.2	80.0
@ 72 m	- Summer 1990	2.94	-0.06	-85.4	73.9
	- Fall 1990	0.97	0.04	-68.0	285.7
	- Winter 1990	3.14	0.34	71.2	194.8
	- Spring 1991	3.17	-0.13	-85.1	357.7
Cape Cod Bay	- Spring 1990	4.25	0.13	-21.5	222.1
@ 4 m	- Summer 1990	3.54	1.12	7.5	179.6
	- Fall 1990	3.17	-0.19	-7.8	208.1
	- Winter 1990	3.59	0.55	-3.1	212.9
Cape Cod Bay	- Spring 1990	4.78	-0.44	-16.5	216.4
@ 25 m	- Spring 1991	3.34	-0.23	-15.0	211.8

TABLE 11 - Least Squares Analysis for the M2 Tidal Currents

Series		Major	Minor	Tilt	Phase
Broad Sound	- Winter 1990	16.11	1.41	49.7	219.8
@ 5 m	- Spring 1991	16.14	-0.27	52.9	217.7
Broad Sound	- Spring 1990	9.21	3.61	83.4	163.9
@ 18 m	- Summer 1990	9.48	4.12	89.7	155.8
	- Fall 1990	9.35	3.13	81.8	168.7
	- Winter 1990	9.96	1.26	65.9	188.6
Boston Buoy	- Winter 1989	9.43	-0.66	77.1	204.0
@ 5 m	- Spring 1990	7.40	-1.01	84.4	198.8
	- Summer 1990	5.35	1.26	-82.0	352.3
	- Winter 1990	9.85	-0.98	76.9	203.9
	- Spring 1991	9.14	-0.15	74.5	196.1
	- Summer 1991	5.44	1.80	-85.8	0.6
Boston Buoy	- Winter 1989	9.10	-0.30	87.1	196.6
@ 23 m	- Spring 1990	7.67	0.36	86.7	200.0
	- Summer 1990	10.19	-0.47	82.1	206.9
	- Fall 1990	11.03	-0.17	87.1	199.8
	- Spring 1991	9.66	-0.28	85.3	203.0
	- Summer 1991	11.22	-0.79	80.3	208.3
Boston Buoy	- Spring 1990	7.01	0.99	-87.3	353.3
@ 33 m	- Summer 1990	8.78	0.42	-76.8	1.3
	- Winter 1990	6.69	0.59	77.0	185.1
	- Spring 1991	7.92	0.56	78.9	179.9
	- Summer 1991	7.94	-0.13	-88.4	1.2
Manomet Point	- Fall 1990	13.39	-1.06	-1.8	212.1
@ 5 m	- Winter 1990	11.26	0.03	-4.9	211.1
	- Spring 1991	13.54	-0.97	-9.3	215.0
Manomet Point	- Fall 1990	7.25	1.27	-1.1	208.6
@ 29 m	- Winter 1990	10.61	0.64	-1.3	207.3
	- Spring 1991	13.28	0.96	4.1	202.2
Race Point	- Fall 1990	46.31	-4.12	63.1	197.1
@ 5 m	- Winter 1990	40.81	3.28	54.3	200.2
	- Spring 1991	45.24	2.18	51.7	202.0
Race Point	- Fall 1990	44.87	-5.36	57.6	197.5
@ 23 m	- Winter 1990	43.47	-1.07	53.1	201.4
Race Point	- Fall 1990	39.30	9.78	54.1	195.0
@ 55 m	- Winter 1990	42.63	0.37	62.0	189.1
	- Spring 1991	41.64	1.29	62.9	184.3
Race Point	- Winter 1990	30.11	0.46	67.9	184.0
@ 60 m	- Spring 1901	25.60	2.02	70.2	177.3
Scituate	- Summer 1990	10.64	-1.38	79.0	173.4
@ 5 m	- Fall 1990	9.05	-0.38	56.0	196.0
	- Winter 1990	7.80	1.21	45.6	202.9
	- Spring 1991	9.55	0.46	48.4	202.7
Scituate	- Spring 1990	2.31	1.66	-33.4	237.1
@ 23 m	- Summer 1990	3.49	1.51	-29.7	236.2
	- Spring 1991	4.25	1.28	-65.2	258.9
Stellwagen Basin	- Fall 1990	20.00	-0.98	-59.7	335.0
@ 75 m	- Winter 1990	13.49	0.87	-88.3	9.9
	- Spring 1991	15.75	-1.74	-76.2	354.8

Stellwagen Basin	- Fall 1990	11.80	1.37	-57.5	328.0
@ 84 m	- Winter 1990	7.94	1.64	-84.6	356.9
	- Spring 1991	9.90	0.52	-64.0	344.0
North Channel	- Summer 1990	6.92	2.46	79.4	230.2
@ 4 m	- Fall 1990	9.63	1.78	82.3	230.7
	- Winter 1990	8.28	1.46	78.6	232.5
North Channel	- Spring 1990	11.60	0.79	-87.0	39.9
@ 25 m	- Summer 1990	10.55	0.72	-86.2	47.7
	- Winter 1990	13.90	2.08	-89.5	50.1
	- Spring 1991	10.57	1.39	88.0	228.3
North Channel	- Summer 1990	10.49	2.38	-83.9	52.3
@ 60 m	- Fall 1990	9.35	4.02	-79.8	56.1
	- Winter 1990	11.21	2.86	84.3	237.4
	- Spring 1991	13.79	2.97	77.0	236.4
Stellwagen Bank-	Summer 1990	23.37	-9.98	83.1	238.0
@ 4 m	- Fall 1990	20.00	-5.24	79.1	227.3
	- Winter 1990	15.36	-1.27	68.6	231.7
	- Spring 1991	29.00	-4.58	71.5	229.9
Stellwagen Bank-	Summer 1990	22.73	1.08	50.1	45.2
@ 25 m	- Fall 1990	16.55	-0.13	51.3	45.0
	- Winter 1990	13.92	-0.16	61.3	42.7
	- Spring 1991	14.98	1.75	66.5	42.0
Stellwagen Basin	- Spr 1990	16.89	-0.45	41.3	321.3
@ 8 m	- Summer 1990	15.61	0.57	39.8	335.7
	- Fall 1990	12.48	-0.80	37.8	258.7
	- Winter 1990	9.68	2.62	72.6	221.3
	- Spring 1991	13.05	2.22	44.6	249.4
Stellwagen Basin	- Spr 1990	10.38	5.98	50.9	313.1
@ 28 m	- Summer 1990	10.53	5.79	54.8	323.3
	- Fall 1990	11.93	0.70	45.2	244.7
	- Winter 1990	12.16	3.20	74.4	220.4
	- Spring 1991	10.51	5.23	56.3	237.7
Stellwagen Basin	- Spr 1990	16.82	0.49	-83.8	84.5
@ 72 m	- Summer 1990	17.20	-1.08	-80.5	100.6
	- Fall 1990	15.59	0.43	-75.0	10.9
	- Winter 1990	13.64	1.54	78.2	211.4
	- Spring 1991	16.56	-0.83	-87.4	18.2
Cape Cod Bay	- Spring 1990	17.75	-0.27	-14.2	230.9
@ 4 m	- Summer 1990	17.00	1.08	8.7	210.7
	- Fall 1990	15.25	0.79	-1.4	221.9
	- Winter 1990	13.45	-0.24	-4.3	222.6
Cape Cod Bay	- Spring 1990	17.06	-0.23	-10.9	228.8
@ 25 m	- Spring 1991	16.45	-0.06	-15.8	229.0

TABLE 12 - Least Squares Analysis for the S2 Tidal Currents

Series		Major	Minor	Tilt	Phase
Broad Sound	- Winter 1990	4.29	1.10	39.1	264.7
@ 5 m	- Spring 1991	2.48	0.39	37.7	272.9
Broad Sound	- Spring 1990	1.00	0.23	10.4	213.5
@ 18 m	- Summer 1990	1.77	0.38	-181.2	4.6
	- Fall 1990	1.65	0.12	6.3	213.8
	- Winter 1990	1.84	0.00	24.0	207.6
Boston Buoy	- Winter 1989	1.56	0.10	16.5	224.7
@ 5 m	- Spring 1990	0.81	-0.22	-198.3	99.1
	- Summer 1990	1.80	-0.66	-183.9	331.7
	- Winter 1990	2.18	-0.32	10.5	226.3
	- Spring 1991	1.41	0.28	7.9	245.9
	- Summer 1991	0.79	-0.34	-218.0	18.4
Boston Buoy	- Winter 1989	1.79	-0.01	6.4	226.2
@ 23 m	- Spring 1990	1.04	-0.06	-186.5	47.4
	- Summer 1990	1.32	-0.01	12.7	221.8
	- Fall 1990	1.99	-0.24	10.6	236.8
	- Spring 1991	1.47	-0.32	12.8	249.5
	- Summer 1991	1.85	-0.36	10.5	233.1
Boston Buoy	- Spring 1990	1.32	0.15	-205.1	14.5
@ 33 m	- Summer 1990	1.30	0.01	4.5	218.1
	- Winter 1990	1.34	0.19	18.3	219.4
	- Spring 1991	1.13	0.22	6.3	223.6
	- Summer 1991	1.12	-0.01	6.9	215.3
Manomet Point	- Fall 1990	1.62	0.02	88.7	248.6
@ 5 m	- Winter 1990	2.11	0.34	-266.6	237.6
	- Spring 1991	1.93	-0.17	-251.9	274.5
Manomet Point	- Fall 1990	1.19	-0.01	88.3	250.6
@ 29 m	- Winter 1990	2.07	0.13	89.2	231.4
	- Spring 1991	2.21	-0.10	87.7	250.0
Race Point	- Fall 1990	6.66	-1.05	28.9	234.3
@ 5 m	- Winter 1990	8.19	-0.74	24.2	224.7
	- Spring 1991	7.04	-1.45	18.0	244.3
Race Point	- Fall 1990	4.72	-0.26	38.2	243.1
@ 23 m	- Winter 1990	7.16	-0.04	37.1	223.8
Race Point	- Fall 1990	4.69	-0.05	20.9	213.5
@ 55 m	- Winter 1990	7.28	0.32	19.7	274.6
	- Spring 1991	5.10	1.31	44.2	241.0
Race Point	- Winter 1990	7.50	-0.12	33.7	225.0
@ 60 m	- Spring 1991	3.53	0.59	35.4	242.1
Scituate	- Summer 1990	2.06	0.13	59.9	293.9
@ 5 m	- Fall 1990	0.81	0.46	-183.2	55.9
	- Winter 1990	1.36	0.53	31.1	227.7
	- Spring 1991	1.20	0.60	9.5	206.3
Scituate	- Spring 1990	0.82	-0.13	-204.3	330.4
@ 23 m	- Summer 1990	1.09	-0.03	23.8	196.9
	- Spring 1991	0.81	-0.65	-207.3	182.0
Stellwagen Basin	- Fall 1990	2.71	-0.13	-213.6	19.9
@ 75 m	- Winter 1990	2.56	0.75	11.1	229.9
	- Spring 1991	1.89	0.40	10.6	241.6

Stellwagen Basin	- Fall 1990	1.52	0.26	-214.4	9.3
@ 84 m	- Winter 1990	1.74	0.67	10.5	220.2
	- Spring 1991	1.39	0.43	3.2	235.2
North Channel	- Summer 1990	2.23	0.39	83.1	274.1
@ 4 m	- Fall 1990	0.70	0.57	13.3	255.7
	- Winter 1990	1.91	-0.07	-189.6	45.9
North Channel	- Spring 1990	1.83	0.24	80.6	339.5
@ 25 m	- Summer 1990	1.75	-0.32	-183.4	49.8
	- Winter 1990	2.66	0.63	-192.1	53.5
	- Spring 1991	2.56	-0.13	10.4	270.1
North Channel	- Summer 1990	3.06	-0.56	-181.3	56.6
@ 60 m	- Fall 1990	1.67	0.15	-193.7	61.6
	- Winter 1990	2.78	0.91	-181.4	52.4
	- Spring 1991	1.98	0.50	0.2	261.0
Stellwagen Bank	- Summer 1990	6.35	-4.36	-190.6	32.3
@ 4 m	- Fall 1990	3.29	-1.10	12.9	254.8
	- Winter 1990	3.46	-0.40	20.4	225.0
	- Spring 1991	3.67	0.21	17.3	261.1
Stellwagen Bank	- Summer 1990	5.24	0.52	43.1	45.9
@ 25 m	- Fall 1990	2.26	0.14	42.7	56.2
	- Winter 1990	2.86	-0.22	38.1	50.7
	- Spring 1991	2.48	0.18	17.9	61.4
Stellwagen Basin	- Spr 1990	1.81	-0.61	41.8	327.4
@ 8 m	- Summer 1990	2.26	0.32	40.7	318.4
	- Fall 1990	0.82	-0.05	80.5	334.3
	- Winter 1990	2.00	1.10	14.5	225.3
	- Spring 1991	1.74	0.09	25.4	255.9
Stellwagen Basin	- Spr 1990	1.66	-0.17	67.7	4.4
@ 28 m	- Summer 1990	1.96	0.81	55.9	342.2
	- Fall 1990	0.93	0.14	29.6	270.6
	- Winter 1990	2.71	1.39	34.7	241.5
	- Spring 1991	1.78	0.20	14.2	252.2
Stellwagen Basin	- Spr 1990	1.61	-0.22	11.4	259.5
@ 72 m	- Summer 1990	2.70	-0.28	0.7	260.7
	- Fall 1990	1.24	0.10	-199.0	84.2
	- Winter 1990	2.71	1.04	24.4	231.6
	- Spring 1991	1.73	0.38	8.9	224.2
Cape Cod Bay	- Spring 1990	2.50	-0.71	-269.0	253.2
@ 4 m	- Summer 1990	2.51	0.01	80.3	217.8
	- Fall 1990	2.20	-0.38	85.9	226.8
	- Winter 1990	1.97	0.46	-260.9	230.9
Cape Cod Bay	- Spring 1990	1.71	0.55	89.8	236.8
@ 25 m	- Spring 1991	2.63	-0.06	-262.7	252.8

TABLE 13 - Least Squares Analysis for the M4 Tidal Currents

Series		Major	Minor	Incline	Phase
Broad Sound	- Winter 1990	1.64	0.09	20.5	186.3
@ 5 m	- Spring 1991	1.76	-0.23	17.7	171.0
Broad Sound	- Spring 1990	0.74	-0.14	30.4	26.1
@ 18 m	- Summer 1990	0.31	0.24	16.0	7.1
	- Fall 1990	0.56	0.04	-7.5	22.0
	- Winter 1990	0.89	-0.25	19.4	64.4
Boston Buoy	- Winter 1989	0.35	0.10	88.1	98.3
@ 5 m	- Spring 1990	0.40	-0.27	55.4	165.6
	- Summer 1990	1.19	-0.94	78.4	98.6
	- Winter 1990	0.36	0.00	60.7	103.0
	- Spring 1991	0.56	-0.04	-76.6	304.2
	- Summer 1991	0.90	-0.45	86.2	114.9
Boston Buoy	- Winter 1989	0.46	0.19	-68.9	283.2
@ 23 m	- Spring 1990	0.41	-0.19	-53.7	261.0
	- Summer 1990	0.52	-0.05	61.0	151.3
	- Fall 1990	0.43	-0.16	81.6	197.5
	- Summer 1991	0.51	0.31	88.0	132.9
Boston Buoy	- Spring 1990	0.49	-0.22	74.6	31.9
@ 33 m	- Summer 1990	0.62	-0.10	-85.1	289.6
	- Winter 1990	0.33	0.00	87.2	84.6
	- Spring 1991	0.72	-0.19	-75.9	261.9
	- Summer 1991	0.49	0.07	-61.8	265.5
Manomet Point	- Fall 1990	1.10	0.14	-0.2	77.0
@ 5 m	- Winter 1990	0.35	0.06	-9.9	124.3
	- Spring 1991	0.30	0.15	-5.1	168.6
Manomet Point	- Fall 1990	0.51	-0.32	33.9	163.6
@ 29 m	- Winter 1990	0.48	-0.22	-31.4	88.7
	- Spring 1991	0.90	-0.26	-11.6	113.8
Race Point	- Fall 1990	2.63	-0.75	-42.4	172.8
@ 5 m	- Winter 1990	2.21	-0.39	-70.5	203.1
	- Spring 1991	2.68	0.61	-36.4	181.2
Race Point	- Fall 1990	1.86	0.17	-27.8	173.5
@ 23 m	- Winter 1990	2.58	-1.10	-1.7	211.0
Race Point	- Fall 1990	4.65	-2.17	-50.9	337.3
@ 55 m	- Winter 1990	2.99	-2.04	66.5	108.9
	- Spring 1991	3.21	-1.40	-74.4	329.2
Race Point	- Winter 1990	1.88	-1.07	-61.6	319.5
@ 60 m	- Spring 1991	3.00	-0.98	-62.3	322.9
Scituate	- Summer 1990	1.31	-0.53	68.6	142.9
@ 5 m	- Fall 1990	0.30	-0.02	-22.6	147.4
	- Winter 1990	0.28	0.04	37.6	89.4
	- Spring 1991	0.29	-0.12	-16.7	124.4
Scituate	- Spring 1990	0.40	-0.18	-8.2	114.8
@ 23 m	- Summer 1990	0.56	0.05	-72.2	157.8
	- Spring 1991	1.25	0.05	76.8	26.9
Stellwagen Basin	- Fall 1990	1.21	-0.76	-87.6	269.2
@ 75 m	- Winter 1990	0.72	-0.41	-6.9	44.7
	- Spring 1991	0.96	-0.43	-61.8	34.0

Stellwagen Basin	- Fall 1990	0.94	-0.64	79.5	86.7
@ 84 m	- Winter 1990	0.32	-0.29	-1.2	45.9
	- Spring 1991	0.71	-0.49	-78.1	4.1
North Channel	- Summer 1990	2.61	-0.89	-67.5	16.3
@ 4 m	- Fall 1990	0.89	-0.43	55.0	129.3
	- Winter 1990	0.48	0.06	67.9	100.4
North Channel	- Spring 1990	1.50	-0.30	-86.8	255.5
@ 25 m	- Summer 1990	1.35	0.19	81.9	100.3
	- Winter 1990	1.19	-0.34	49.5	137.3
	- Spring 1991	0.85	0.11	80.9	137.9
North Channel	- Summer 1990	0.31	0.02	16.9	201.1
@ 60 m	- Fall 1990	0.49	-0.35	-62.1	131.6
	- Winter 1990	0.45	-0.07	-12.2	158.2
	- Spring 1991	0.72	-0.69	6.7	155.6
Stellwagen Bank	- Summer 1990	2.69	-1.19	78.9	110.4
@ 4 m	- Fall 1990	0.86	0.13	-44.5	289.3
	- Winter 1990	0.95	0.52	-49.1	261.9
	- Spring 1991	2.35	-0.38	50.2	177.6
Stellwagen Bank	- Summer 1990	1.84	0.13	19.8	315.1
@ 25 m	- Fall 1990	1.85	0.21	14.6	323.2
	- Winter 1990	0.76	0.27	28.4	345.4
	- Spring 1991	1.09	-0.10	35.6	292.4
Stellwagen Basin	- Spr 1990	1.86	-1.31	-3.3	79.7
@ 8 m	- Summer 1990	1.11	-0.76	-46.0	50.1
	- Fall 1990	0.74	-0.34	-15.8	283.3
	- Winter 1990	0.29	-0.04	-57.4	296.6
	- Spring 1991	1.11	-0.26	-76.2	268.6
Stellwagen Basin	- Spr 1990	2.00	-1.74	-61.4	98.3
@ 28 m	- Summer 1990	1.39	-0.76	56.8	262.8
	- Fall 1990	1.33	-0.67	-79.3	311.7
	- Winter 1990	0.41	0.05	-62.7	306.2
	- Spring 1991	1.57	-0.53	85.9	121.3
Stellwagen Basin	- Spr 1990	1.07	-0.65	50.2	318.0
@ 72 m	- Summer 1990	0.81	0.41	26.7	106.0
	- Fall 1990	0.76	-0.20	44.0	111.3
	- Winter 1990	0.40	-0.19	-21.6	82.0
	- Spring 1991	0.58	-0.22	-57.0	87.5
Cape Cod Bay	- Spring 1990	0.56	-0.44	-47.2	157.9
@ 4 m	- Summer 1990	0.90	0.05	3.7	116.0
	- Fall 1990	0.62	-0.28	-37.7	193.2
	- Winter 1990	0.86	0.01	36.8	139.1
Cape Cod Bay	- Spring 1990	0.74	-0.08	-20.6	143.1
@ 25 m	- Spring 1991	0.73	-0.22	-86.9	133.3

TABLE 14 - Least Squares Analysis for the M6 Tidal Currents

Series		Major	Minor	Incline	Phase
Broad Sound	- Winter 1990	0.69	0.07	23.5	68.2
@ 5 m	- Spring 1991	0.91	0.32	28.0	46.2
Broad Sound	- Spring 1990	0.74	-0.30	72.2	2.6
@ 18 m	- Summer 1990	0.99	-0.28	50.0	16.2
	- Fall 1990	0.79	-0.32	36.8	1.9
	- Winter 1990	0.74	-0.23	44.3	350.3
Boston Buoy	- Winter 1989	0.46	0.10	65.8	347.5
@ 5 m	- Spring 1990	0.39	0.01	86.1	336.8
	- Summer 1990	0.68	-0.27	35.2	9.0
	- Winter 1990	0.47	0.08	59.5	352.8
	- Spring 1991	0.67	0.05	48.4	5.2
	- Summer 1991	0.75	-0.12	40.5	12.1
Boston Buoy	- Winter 1989	0.42	0.10	64.4	343.9
@ 23 m	- Spring 1990	0.34	0.13	59.1	335.4
	- Summer 1990	0.48	0.07	51.7	354.4
	- Fall 1990	0.27	0.00	-65.2	144.9
	- Winter 1990	0.33	0.14	59.9	327.4
	- Spring 1991	0.55	0.13	61.4	327.8
	- Summer 1991	0.30	0.12	73.8	336.0
Boston Buoy	- Spring 1990	0.57	0.11	66.7	340.2
@ 33 m	- Summer 1990	0.56	-0.04	71.0	12.8
	- Winter 1990	0.42	0.09	56.2	350.1
	- Spring 1991	0.69	-0.03	60.2	350.5
Manomet Point	- Fall 1990	1.54	0.09	-8.2	28.0
@ 5 m	- Winter 1990	1.09	0.04	-6.7	10.8
	- Spring 1991	1.33	0.08	-17.3	24.5
Manomet Point	- Fall 1990	1.01	-0.04	-11.4	24.8
@ 29 m	- Winter 1990	1.00	0.04	-12.5	19.1
	- Spring 1991	1.57	-0.06	-6.6	33.4
Race Point	- Fall 1990	2.27	0.51	51.4	18.9
@ 5 m	- Winter 1990	2.51	0.05	67.6	18.0
	- Spring 1991	2.65	0.33	47.4	17.0
Race Point	- Fall 1990	3.96	0.00	52.6	40.4
@ 23 m	- Winter 1990	2.92	0.34	52.6	44.0
Race Point	- Fall 1990	3.38	-0.94	59.0	27.5
@ 55 m	- Winter 1990	3.32	-0.58	53.3	34.8
	- Spring 1991	3.68	-0.93	54.8	36.9
Race Point	- Winter 1990	2.30	-0.26	56.7	0.4
@ 60 m	- Spring 1991	1.97	-0.39	52.7	3.5
Scituate	- Summer 1990	0.70	0.05	21.8	13.4
@ 5 m	- Fall 1990	0.81	0.09	13.6	11.0
	- Winter 1990	0.91	0.01	1.8	12.9
	- Spring 1991	0.95	-0.13	1.6	17.2
Scituate	- Spring 1990	0.33	0.27	-32.5	0.6
@ 23 m	- Summer 1990	0.93	-0.07	4.4	1.9
	- Spring 1991	0.73	-0.01	8.9	356.7
Stellwagen Basin	- Fall 1990	1.55	-0.78	38.0	356.0
@ 75 m	- Winter 1990	0.71	-0.04	35.8	7.4
	- Spring 1991	0.71	0.11	19.5	12.6

Stellwagen Basin	- Fall 1990	1.21	-0.13	41.0	5.7
@ 84 m	- Winter 1990	0.42	0.02	37.2	355.9
	- Spring 1991	0.43	0.09	87.7	306.4
North Channel	- Summer 1990	1.09	0.26	-74.5	214.4
@ 4 m	- Fall 1990	0.53	-0.05	27.8	80.1
	- Winter 1990	0.64	-0.17	27.9	88.4
North Channel	- Spring 1990	0.37	-0.06	28.2	94.4
@ 25 m	- Summer 1990	0.63	-0.20	52.9	86.0
	- Winter 1990	0.91	-0.42	63.7	103.9
	- Spring 1991	0.83	-0.06	58.4	73.4
North Channel	- Summer 1990	1.18	0.00	43.4	98.5
@ 60 m	- Fall 1990	0.85	0.10	61.5	73.6
	- Winter 1990	0.60	-0.08	58.4	84.7
	- Spring 1991	1.19	-0.33	45.9	109.5
Stellwagen Bank-	Summer 1990	2.05	-1.13	58.4	70.5
@ 4 m	- Fall 1990	2.16	-0.73	42.6	76.0
	- Winter 1990	0.90	0.18	33.8	71.6
	- Spring 1991	2.34	-0.18	38.8	96.9
Stellwagen Bank-	Summer 1990	1.69	0.04	11.5	273.9
@ 25 m	- Fall 1990	0.52	0.07	31.2	282.0
	- Winter 1990	1.31	-0.12	34.5	251.1
	- Spring 1991	1.66	-0.08	52.7	246.0
Stellwagen Basin	- Spr 1990	0.38	0.28	-29.2	71.1
@ 8 m	- Summer 1990	0.64	0.13	-31.3	87.3
	- Fall 1990	0.50	0.13	2.7	114.7
	- Winter 1990	0.55	0.00	23.8	68.7
	- Spring 1991	0.61	0.11	42.5	91.2
Stellwagen Basin	- Spr 1990	0.98	-0.33	25.7	331.0
@ 28 m	- Summer 1990	1.17	-0.06	30.1	349.2
	- Fall 1990	0.49	-0.10	32.5	65.0
	- Winter 1990	0.69	-0.12	22.3	76.2
	- Spring 1991	0.87	-0.12	34.6	88.2
Stellwagen Basin	- Spr 1990	1.12	-0.10	28.0	296.3
@ 72 m	- Summer 1990	1.15	-0.35	10.3	336.8
	- Fall 1990	1.07	-0.40	27.2	49.5
	- Winter 1990	0.54	-0.05	9.3	73.6
	- Spring 1991	1.13	-0.15	13.4	84.3
Cape Cod Bay	- Spring 1990	1.44	0.08	-21.8	97.4
@ 4 m	- Summer 1990	1.91	0.09	-16.7	115.6
	- Fall 1990	1.54	0.33	-10.3	98.4
	- Winter 1990	1.21	-0.02	-10.3	63.9
Cape Cod Bay	- Spring 1990	1.67	-0.10	-9.9	97.2
@ 25 m	- Spring 1991	2.01	-0.12	-21.7	103.5

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REPORT DOCUMENTATION PAGE	1. REPORT NO. WHOI-92-35	2.	3. Recipient's Accession No.

4. Title and Subtitle Tides of Massachusetts and Cape Cod Bays	5. Report Date September 1992 6.
7. Author(s) J. D. Irish and R.P. Signell	8. Performing Organization Rept. No. WHOI-92-35
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, Massachusetts 02543	10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) (G)
12. Sponsoring Organization Name and Address U.S. Geological Survey	13. Type of Report & Period Covered Technical Report 14.

15. Supplementary Notes

This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept., WHOI-92-35.

16. Abstract (Limit: 200 words)

The Massachusetts Bays Program made bottom pressure and water velocity observations in Massachusetts and Cape Cod Bays during 1990 and 1991. In the Bays, the sea surface elevation appeared to rise and fall in phase with equal amplitudes at each diurnal or semidiurnal tidal frequency. There is some amplification in Boston and Provincetown harbors. The semidiurnal tides (particularly the M2 constituent) dominate. Massachusetts and Cape Cod Bays are part of the Gulf of Maine/Bay of Fundy system which is resonant near the semidiurnal frequency. This resonance amplifies the importance of the semidiurnal tides so that diurnal and higher harmonic tides become negligible. The sea level tides force currents which move with the same frequencies, but whose amplitudes are affected by the bathymetry. The strongest currents exist in the channel between Race Point and Stellwagen Bank where tidal currents exceed 1 knot. Analysis of current records for their tidal signal is complicated by internal tides which contaminate the records. These internal waves at tidal frequency exist on the stratification in the water column, and disappear during winter well-mixed times. At other times they must be considered as a significant source of energy for mixing and resuspension of sediments.

17. Document Analysis a. Descriptors

tides
currents
internal waves

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Approved for public release; distribution unlimited.	UNCLASSIFIED	66
	20. Security Class (This Page)	22. Price

(See ANSI-Z39.18) *See Instructions on Reverse* OPTIONAL FORM 272 (4-77)
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